

# Hydrogen Film Cooling With Incident and Swept-Shock Interactions in a Mach 6.4 Nitrogen Free Stream

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## Abstract

*The effectiveness of slot film cooling of a flat plate in a Mach 6.4 flow with and without incident and swept oblique shock interactions was experimentally investigated. Hydrogen was the primary coolant gas, although some tests were conducted using helium as the coolant. Tests were conducted in the Calspan 48-Inch Shock Tunnel with a nitrogen flow field to preclude combustion of the hydrogen coolant gas. A two-dimensional highly instrumented model developed in a previous test series was used. Parameters investigated included coolant mass flow rate, coolant gas, local free-stream Reynolds number, incident oblique shock strength, and a swept oblique shock. Both gases were highly effective coolants in undisturbed flow; however, both incident and swept shocks degraded that effectiveness.*

## Introduction

Film cooling has been proposed as a means of thermal protection to reduce the scramjet combustor wall heating loads and the fuel mass required for regenerative cooling alone. In this concept, some of the regeneratively heated hydrogen fuel is injected at a supersonic velocity parallel to the wall through small slots to provide a buffer layer between the hot engine core flow and the structure. In addition to thermal protection, film cooling may improve engine performance by reducing skin friction and providing thrust in the high Mach number operating range. A coordinated government and industry study was conducted (refs. 1 and 2) to define film cooling technology for application to scramjet engines and to identify areas that require further data. The experimental effort reported herein is an outgrowth of this study.

Some aerothermal problems associated with hypersonic flows are summarized in reference 3. These problems include determining heat fluxes in the regions of incident-shock (two-dimensional) and swept-shock (three-dimensional) interactions with turbulent boundary layers. An oblique shock incident on a turbulent boundary layer forms a two-dimensional flow field with a separate flow region, a "lambda" shock structure (the incident and separation shock combination), and a reattachment (reflected) shock (fig. 1(a)). The interaction region becomes steady state and the extent of the separation region depends on the shock strength. An oblique shock that is swept across a turbulent boundary layer forms a three-dimensional flow field with a lambda shock and separation region structure as shown in figure 1(b) (from ref. 4). However, in the swept-shock configuration, the entire interaction region grows in a quasi-conical manner from the shock origin (ref. 4). The separated flow region becomes a spiral vortex that grows with entrained mass (fig. 1(c)). Results for a swept-shock interaction on an uncooled flat plate at similar flow conditions are reported in reference 5. These results show that heat flux and pressure rises begin 2 in. upstream and reach post-shock levels 2 in. downstream relative to inviscid shock location.

Both the two-dimensional and three-dimensional flow structures are present in a scramjet combustor and are a major cause of high local heat fluxes. Film cooling is one method under consideration for reducing these fluxes. However, the addition of a coolant film in these shock and boundary-layer interactions further complicates the understanding of the fluxes.

A joint experimental two-stage program was developed by Langley Research Center (LaRC) and Calspan-University at Buffalo Research Center (CUBRC) to study film cooling for scramjet applications. The tests were conducted in the Calspan 48-Inch Shock Tunnel. (See ref. 6 for a detailed description of the test facility.) The nominal test conditions were Mach 6.4 flow at  $R_\infty = 7.4 \times 10^6/\text{ft}$ ,  $T_0 = 2189^\circ\text{R}$ , and  $p_0 = 2252$  psia. Stage 1 tests (refs. 7 to 9) used helium injected at Mach 3 as the coolant gas and determined some of the fundamental phenomena that govern supersonic film cooling in a two-dimensional noncombusting environment. Parameters of the study included coolant delivery pressure, coolant slot height, lip thickness, and incident shock strength. Results for undisturbed flow were as follows:

1. Coolant pressure matched to the local boundary-layer edge pressure is most effective.
2. Larger slot heights (0.120 in.) are more effective than smaller slot heights (0.080 in.).
3. Lip thickness in the range of 0.020 to 0.205 in. has no net effect on film cooling. Data for the interactions between the film-cooling layer and the incident shock show that incident shocks degrade film-cooling effectiveness. However, these data also suggest multiple-slot film-cooling designs to reestablish the film-cooling layer downstream of a shock.

The test series reported herein, stage 2, uses hydrogen that is injected at Mach 2.7 as the primary coolant gas, although some tests with helium coolant were conducted at Mach 3. To preclude combustion when the coolant was hydrogen, the free-stream test medium for

all tests was nitrogen. The following effects were investigated:

1. Coolant mass flow rate with undisturbed flow for both hydrogen and helium coolants.
2. Incident-shock interactions for shock turning angles of 2.5°, 5.0°, and 7.5° with hydrogen coolant at a delivery pressure matched to free-stream pressure.
3. Incident-shock interactions for shock turning angles of 2.5° and 5.0° with hydrogen coolant at a delivery pressure matched to free-stream pressure and with a reduced local Reynolds number.
4. Swept-shock interactions for a shock turning angle of 5.0° with no coolant and with hydrogen coolant at delivery pressures matched to both the preshock and postshock pressures. The test matrix is shown in table I.

## Symbols

|          |   |
|----------|---|
| $c_v$    | specific heat, Btu/lbm-°R   |
| $g_c$    | acceleration due to gravity,<br>32.2 lbm-ft/lbf-sec <sup>2</sup>                  |
| $J$      | mechanical equivalent of heat, 778.16 ft-lbf/Btu                                  |
| $M$      | Mach number   |
| $m$      | mass flow rate, lbm/sec-in <sup>2</sup>   |
| $p$      | static pressure, psia   |
| $p_0$    | total pressure, psia  |
| $q$      | heat flux, Btu/ft <sup>2</sup> -sec   |
| $q_0$    | flat-plate heat flux, Btu/ft <sup>2</sup> -sec                                    |
| $Q_0$    | Fay and Riddell heat transfer to 3-in-diameter cylinder, Btu/ft <sup>2</sup> -sec |
| pos      | position  |
| $R$      | Reynolds number at coolant slot   |
| $s$      | slot height, in.  |
| $T$      | temperature, °R   |
| $T_0$    | total temperature, °R   |
| $t$      | lip thickness, in.  |
| $V$      | velocity, ft/sec  |
| $x$      | streamwise distance from coolant slot, in.  |
| $y$      | transverse distance from plate centerline, in.                                    |
| $\gamma$ | ratio of specific heats   |
| $\delta$ | boundary-layer thickness, in.   |
| $\mu$    | viscosity, lbm/ft-sec   |
| $\nu$    | kinematic viscosity, ft <sup>2</sup> /sec   |

Subscripts:

|          |                     |
|----------|---------------------|
| $c$      | coolant             |
| $e$      | boundary-layer edge |
| $\infty$ | free stream         |

## Apparatus and Tests

### Facility

The tests were conducted in the Calspan 48-Inch Shock Tunnel at a nominal free-stream Mach number of 6.4 with  $R_\infty = 7.4 \times 10^6/\text{ft}$ ,  $T_0 = 2189^\circ\text{R}$ , and  $p_0 = 2252$  psia (table II). Nitrogen was used as the free-stream test gas to preclude combustion when hydrogen coolant gas was used. The facility and its operation and test envelope are described in reference 6. Tunnel runs had steady flow times on the order of 5 msec.

### Model

The model consisted of a sharp leading-edge flat plate, a coolant distribution system with a rearward-facing coolant injection slot, instrumented downstream plates, an adjustable horizontal oblique-shock generator, and a vertical oblique-shock generator.

Configurations with 15-in-long and 28-in-long sharp-leading-edge instrumented foreplates combined with the coolant distribution section provided total leading-edge-to-coolant-slot foreplate lengths of 19 in. and 32 in., respectively. This assembly was sting mounted in the facility at zero angle of attack. Free-stream Reynolds numbers at the coolant slot locations based on length from the leading edge were  $11.75 \times 10^6$  and  $19.80 \times 10^6$ , respectively. These Reynolds numbers provide naturally transitioned turbulent boundary layers at the coolant injection location. Analyses from the Boundary Layer Integral Matrix Procedure (BLIMP code version K, ref. 10), with a momentum integral thickness Reynolds number of 700, predicted boundary-layer thicknesses  $\delta$  of 0.34 in. and 0.44 in., at the coolant slot locations.

The two-dimensional film cooling nozzles and the related coolant distribution system (fig. 2), were designed in stage 1 for uniform injection of helium at Mach 3 by using a sequential method-of-characteristics and Navier-Stokes analysis. The sequence included inviscid contour prediction, viscous analysis, contour modification for displacement thickness, and final viscous analysis. The computed helium flow was laminar with an exit boundary-layer thickness of 0.024 in. Two nozzle sets with slot heights  $s$  of 0.080 in. and 0.120 in. and a lip thickness  $t$  of 0.020 in. were fabricated. The

0.020-in. lip was considered a lower practical limit for an internally cooled structure. Forty nozzles spanned the 18-in. width of the model. The nozzles were fed, in groups of eight, from five individual high-pressure storage bottles through fast-acting valves and primary metering orifices. Coolant gas from the storage bottles entered the coolant distribution system and was channeled to the individual nozzles through equal-length flow paths and secondary metering orifices. (See fig. 2(c).) Based on stage 1 results, which show better cooling effectiveness for the larger slot height, stage 2 utilized only the 0.120-in. cooling nozzles. Adapting the nozzles for use with hydrogen coolant required the replacement of primary metering orifices in each circuit with smaller orifices to account for the difference in properties of helium and hydrogen. Repeating the original design analysis sequence for hydrogen indicated that the nozzles would still operate satisfactorily (the gas properties used in the analysis are shown in table III). Schlieren photographs (not shown) of the nozzle discharge, taken through an optical window installed in place of the instrumented plate, suggest weak internozzle wake structures and relatively uniform coolant flow. The model assembly was modified for stage 2 to incorporate O-ring seals at mating points to reduce coolant gas leakage. Coolant leakage from the lap joint (fig. 2(c)) was not totally eliminated but did not appear to be significant. The range of coolant delivery pressure (measured at the coolant nozzle exit) as a function of the boundary-layer edge pressure at the slot location  $p_c/p_e$  was 0.5 to 2.0 (with the associated mass flow rates of 0.163 to 1.580 lbm/sec-in<sup>2</sup>). Nominal coolant flow conditions (table II) were  $M_c = 2.7$  and  $T_{0,c} = 536^\circ\text{R}$  for hydrogen coolant and  $M_c = 3.0$  and  $T_{0,c} = 536^\circ\text{R}$  for helium coolant.

The plates downstream of the coolant nozzles were instrumented with streamwise rows of thin-film thermometers and pressure gauges near the centerline (fig. 3). The thin-film thermometers, developed by Calspan, were platinum resistance thermometers on Corning Pyrex substrates. The thermometers were spaced 0.1 to 1.3-in. apart, with the finer spacing in the slot and shock interaction regions. Accuracy of these thin-film thermometers, including the uncertainties associated with the gauge calibration and data recording equipment, is estimated to be  $\pm 5$  percent for the heating levels encountered in these tests.

Calspan-designed lead zirconium titanate piezoelectric pressure transducers capable of following fluctuations of up to 15 kHz were used to obtain mean pressure data. The frequency pressure gauges were spaced from 0.6 to 1.3 in. apart in two rows offset from the centerline (fig. 3). The system for recording the data output from the temperature and pressure instrumentation, filtering

the data, and processing the data is described in reference 6.

An adjustable horizontal shock generator system (fig. 4) produced oblique shocks that were made incident on the instrumented plate 2 in. downstream of the coolant slot (based on inviscid theory). Flow turning angles of  $2.5^\circ$ ,  $5.0^\circ$ , and  $7.5^\circ$ , with associated shock angles of  $10.64^\circ$ ,  $12.56^\circ$ , and  $14.70^\circ$ , were investigated.

A 17-in. by 8-in. vertical shock generator was mounted on the foreplate to produce a  $5^\circ$  flow turning angle swept shock across the instrumented plates (fig. 5). The shock generator was translated in the y-direction to move the shock with respect to the lines of instrumentation. Four shock-nozzle y-direction crossing locations (based on inviscid theory) were tested, and the corresponding downstream location (x-direction) of the shock-instrumentation intersections are shown. The two lines of pressure instrumentation are offset from the centerline (fig. 3) and result in different shock crossing locations than the thin-film thermometers.

### Test Procedures

Coolant injection system performance was determined in the test facility at the test static pressure (1 psia) without tunnel flow. Nozzle mass flow rates were calibrated against reservoir supply pressures. Pressure measurements that were made upstream of the primary orifice and at the nozzle plenum (downstream of the secondary orifice), throat, and exit planes during initial nozzle calibration runs indicated that the flow within the distribution system was uniform. The ratio of coolant delivery pressure to the boundary-layer edge pressure was from 0.5 to 2.0. Mass flow rates (table II) were determined from the numerical slope of the reservoir pressure versus time history over a selected period of constant flow. This method of calculating mass flow rates provided more accurate results than the method that uses the initial-to-peak pressure slope (stage 1). The flow area includes lip thickness and sidewall thickness. Coolant flow conditions and mass flow rates are shown in table II. Coolant injection nozzles were sealed with aluminum tape for tests with no coolant flow to prevent backflow into the coolant distribution system.

The film-cooling tests began by initiating coolant flow in advance of tunnel flow to establish steady-state conditions in the coolant nozzles. Tunnel flow was then initiated with approximately 5 msec of steady-state flow. Thin-film thermometer and pressure data were recorded on a data acquisition system and were reduced as described in reference 6. Data reduction averaged the instrumentation output over a selected 2-msec interval of the 5-msec steady-state flow time. Heat fluxes were

determined from the thin-film thermometer data by using a semi-infinite slab approximation (ref. 6).

### Reference Condition

Flat-plate (no rearward-facing step) reference conditions for heat-flux and pressure distributions over the full length of the model were established in stage 1 and are shown in figure 6. These data represent two runs, one with dense instrumentation on the foreplate and the other with dense instrumentation in the test region. A polynomial fit of the heat-flux distribution (ref. 8 and fig. 6(a)) results in the following second-order curve:

$$q(x) = 9.14 - 0.119x + 0.0034x^2 \quad (1)$$

This heat-flux distribution is used as the reference condition for undisturbed flow cooling effectiveness results. The pressure distribution (fig. 6(b)) in the test region is uniform.

### Discussion of Results

Experimentally determined heat-flux and pressure distributions downstream of the coolant injection slot are shown first in tabulated form and then as individual plots. The tabulated data have been normalized to the undisturbed flow case with no coolant by using the Fay and Riddell heat transfer to a 3-in-diameter cylinder and stagnation pressure ratios as shown in table I. The smoothed curve was computed by averaging each data point with the linear interpolation of the value from its two nearest neighbors. This smoothing, at the risk of attenuating real local maximum and minimum values of the data, removes some of the data scatter that is inherent in the flow-field nonuniformity. These smoothed curves are used to facilitate direct comparison of data sets in the text. Heat-flux distributions over the foreplate for all tests show that run-to-run variations are less than  $\pm 5$  percent.

#### Coolant Mass Flow Effects

Heat-flux and pressure distribution data for flow with no coolant and for both hydrogen and helium coolants delivered over a range of flow rates are listed in tables IV and V, respectively. The data are plotted as follows:

1. Baseline heat flux with no coolant and the pressure data are shown in figure 7.
2. Hydrogen and helium coolant heat-flux data are shown in figures 8 and 9, respectively.
3. Hydrogen and helium coolant pressure data are shown in figures 10 and 11, respectively.

Data from the flow configuration with no coolant (fig. 7) show the low heat-flux region in the separated flow region immediately downstream of the rearward-facing step followed by a peak heat flux when the flow reattaches. After reattachment, the heat flux and pressure essentially return to the flat-plate value about ten slot heights (1.2 in.) downstream; there is some oscillation as the disturbance is damped out. There are two areas with anomalies that are probably not associated with the primary phenomenon under consideration. The first occurs in the heat flux approximately 5.5 in. from the slot and may originate at the joint between the instrumented plates. This joint was initially aligned and smoothed with wax, but may be displaced during a test by a pressure differential between the top and bottom of the plate. Pressure instrumentation in this region is not sufficient to capture the disturbance. The second anomaly is a pressure rise 10 to 14 in. downstream from the slot (out of view of the tunnel window) that is probably caused by an extraneous disturbance, such as a shock, in the flow. This pressure rise plainly appears in all the pressure data and appears less distinctly in the heat-flux data.

Heat-flux data with hydrogen and helium film coolants in an undisturbed flow are compared in figures 12(a) and 12(b), respectively. These data show that the effects of imbedded shock and expansion regions that result from the various coolant delivery pressures,  $0.5 \leq p_c/p_e \leq 2.0$ , are confined to the near-slot region (i.e.,  $x/s < 25$ , where  $x = 3$  in.). Downstream of this region the reduction in heat flux is a function of the coolant mass flow rate only. A diminishing return on heat-flux reduction by increasing coolant mass flow rates is readily apparent in the data and suggests that a given coolant mass may be more effectively used by injecting through a series of small slots spaced along the downstream direction rather than a single larger slot (also noted from the stage 1 results, ref. 8).

A comparison of heat flux for both hydrogen and helium coolant gases at the same mass flow rate,  $0.662 \text{ lbm/sec-in}^2$ , is shown in figure 12(c). The data for helium coolant at this flow rate was obtained by interpolating the bracketing flow rates. The interpolated delivery pressure ratio  $p_c/p_e$  for helium is 0.81 and 2.0 for hydrogen; however, as noted previously, the effect of delivery pressure is confined to the near-slot region. The downstream region shows that for the same mass flow rate, hydrogen coolant reduced the local heat flux 10 to 20 percent more than helium coolant.

There have been several attempts (e.g., refs. 11 and 12) to develop correlations for film cooling data. The following basic correlation is used:

$$1 - q/q_0 = (x/s) (m_c/m_\infty)^{-0.8} \quad (2)$$

where  $q_0$  is the flat-plate reference heating rate,  $m_c$  is coolant mass flow per unit area, and  $m_\infty$  is the free-stream mass flow per unit area. This correlation is applied to the hydrogen and helium data in figure 13(a) and collapses the data for each gas into a single curve. However, the two gases have distinctly different curves. Suggestions of other parameters to be included in the correlation are made in reference 12. A variation of the basic correlation suggested in the present study uses a ratio of the energy flux (internal energy plus kinetic energy,  $(c_v T + V^2/2g_c J) m$ ) of the two streams instead of mass flux alone, as follows:

$$1 - q/q_0 = (x/s) \left\{ \frac{[c_v T_c + (V_c^2/2g_c J)] m_c}{[c_v T_\infty + (V_\infty^2/2g_c J)] m_\infty} \right\}^{-.8} \quad (3)$$

This correlation collapses the data for both coolant gases into a single curve (fig. 13(b)).

### Incident Shock Effects

Heat-flux and pressure distribution data for horizontal-wedge-induced shocks with flow turning angles of  $2.5^\circ$ ,  $5.0^\circ$ , and  $7.5^\circ$  incident on a hydrogen coolant film with a mass flow rate of  $0.260 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.0$ ) are listed in tables VI and VII. In addition to the base free-stream Reynolds number of  $19.8 \times 10^6$ , based on the foreplate length to the coolant slot, data were taken at a free-stream Reynolds number of  $11.75 \times 10^6$  ( $2.5^\circ$  and  $5.0^\circ$  shocks only). The heat-flux and pressure data for the base Reynolds number are shown in figures 14 and 15. The heat-flux and pressure data for the reduced Reynolds number are shown in figures 16 and 17.

Heat-flux and pressure data for the base Reynolds number cases are summarized in figure 18. If the flow were inviscid, the shocks would have impinged on the plate approximately 2 in. downstream of the slot and there would have been an instantaneous jump to the post-shock conditions. However, viscous effects alone stretch the interaction region to several inches in length (ref. 7), and the presence of the cooling layer stretches it several more inches. The values of downstream heat flux for the  $5.0^\circ$  and  $7.5^\circ$  shocks are only 6 to 8 percent less than the heat flux with no coolant (ref. 7). Interaction with an expansion fan from the trailing edge of the shock generator caused the sharp drop in the  $7.5^\circ$  shock heat flux starting about 14 in. from the slot. Post-shock pressure levels with  $5.0^\circ$  and  $7.5^\circ$  shocks were approximately the same as for shock results with no coolant (ref. 7), but all post-shock pressures were approximately 20 percent higher than inviscid theory predictions (fig. 15).

Heat-flux and pressure data for the reduced Reynolds number ( $11.75 \times 10^6$ ) are compared with those for the base Reynolds number ( $19.8 \times 10^6$ ) in figures 19 and 20. This 40-percent reduction in Reynolds number (the result of a shortened foreplate) and its associated reduction in free-stream boundary-layer thickness from 0.44 in. to 0.34 in. had no significant effect on either the heat-flux distribution or the pressure distribution downstream of the coolant slot (except for the anomalous excursion in heat flux downstream of the interplate joint at 5 in.).

A schlieren photograph and flow-field schematic for the  $5.0^\circ$  incident shock at the reduced Reynolds number are shown in figure 21 and are typical of all the incident shock tests. The photograph, taken through a 16-in.-diameter window, has the coolant slot approximately centered. Two coolant nozzle assembly joints ahead of the slot still leaked some hydrogen coolant, but the disturbance degenerated to a Mach wave in the free stream so that it had minimal effect on the flow. The incident shock and reflected shocks, as well as a weak shock that appears to originate from the joint between the 5-in. and 12-in. instrumented plates (corresponds to the data fluctuations previously noted), are identified. Thinning of the boundary layer by the incident shock is evident from the dark and light regions near the wall and may indicate the thickness of the hydrogen layer and mixing layer.

### Swept-Shock Effects

Heat-flux and pressure distribution data for a  $5^\circ$ -turning-angle, vertical-wedge-induced shock sweeping across the instrumented region are listed in tables VIII and IX. The data include flow with no coolant and with hydrogen coolant films with mass flow rates of  $0.260 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.0$ ) and  $0.662 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 2.0$ ). No-coolant data are shown in figures 22 and 23; low-coolant flow-rate data are shown in figures 24 and 25; higher flow-rate data are shown in figures 26 and 27. The shock generator was located in four different spanwise positions on the plate (fig. 5), so that the shock crossed the coolant slots at different points as indicated. The thin-film temperature gauges are located near the model centerline, but pressure instrumentation is offset in two rows (fig. 3). As a result of these offsets, the pressure distributions for position 3 gauges 1 to 9 and position 4 gauges 10 to 16 correspond to the heat-flux distribution for position 2, and the pressure distribution position 4 gauges 1 to 9 correspond to the heat-flux distribution for position 3. These data form a complete set of coincident heat-flux and pressure results that are equivalent to the configuration with the shock crossing the coolant slots at the centerline ( $y = 0.0$ ).

and are shown in figure 28 for each of the coolant flow conditions.

Heat-flux distributions for the swept shock with no coolant (fig. 22) are compared with the undisturbed (no-shock) no-coolant flow distributions. The point at which the shock crosses the centerline instrumentation is labeled, except for position 1, where the shock crosses the centerline ahead of the coolant slot and the entire instrumentation region is behind the shock. Heat flux begins to rise behind the shock intersection and appears to reach a maximum and then decline. The location of the maximum moves downstream as the shock crossing point moves downstream. The decline in heat flux after the maximum is reached is the result of boundary-layer interaction with the expansion fan from the trailing edge of the shock generator (fig. 5). The pressure distributions show no increase that is directly related to the shock location (fig. 23); the pressure level seems to rise behind the slot to some uniform level that depends on the shock location—the farther downstream the shock the lower the uniform pressure level. Only when the shock is in position 1 does the downstream pressure level approach the predicted inviscid pressure level (except for the previously noted extraneous pressure rise at approximately 13 in. downstream). These behaviors suggest that the spanwise pressure gradient, induced in the free stream by the swept shock, is driving a three-dimensional relief of the flow through the boundary layer that retards the heat-flux and pressure rises.

Heat-flux and pressure distributions for the 5°-flow-turning-angle, swept shock with hydrogen coolant film and  $m_c = 0.260$  lbm/sec-in<sup>2</sup> ( $p_c/p_e = 1.0$ ), (figs. 24 and 25), are compared with the equivalent undisturbed flow distributions and with the results of the 2.5°-incident oblique shock which, because of shock reflection, results in the same total pressure rise ( $\Delta p = 1.03$  psia). The coolant delivery pressure,  $p_c/p_e = 1.0$ , is matched to the preshock free-stream pressure. Coolant flow, in both swept and incident shock configurations, reduces the heat flux in the near-slot region,  $x \leq 5$  in., to nearly zero. The 5°-swept-shock heat flux rises to the undisturbed value (fig. 22) between  $5 < x < 10$  in., but the 2.5°-incident-shock heat flux does not reach the undisturbed values until  $x > 15$  in. The significant difference in heat flux between these two configurations with the same pressure rise can be attributed to the growth of the separated flow region and the spiral vortex formed at the base of the swept shock. Fed by the third component of velocity, a steady supply of high-temperature fluid from the free stream is transported through the boundary layer to the wall region; conversely, the coolant film is dispersed into the mainstream flow. Pressure distributions with coolant flow (fig. 25)

are virtually the same as the no-coolant pressure distributions (fig. 23).

Heat-flux and pressure distributions for the swept shock with hydrogen coolant film with a mass flow rate of 0.662 lbm/sec-in<sup>2</sup> ( $p_c/p_e = 2.0$ ) are compared with the equivalent undisturbed flow distributions in figures 26 and 27. The coolant delivery pressure,  $p_c/p_e = 2.0$ , is matched to the post-shock free-stream pressure. This higher coolant mass flow slightly extends the region of near-zero heat-flux and retards the rise to the undisturbed level. Otherwise, the performance is similar to the lower coolant mass flow rate. Again, the pressure distributions are virtually the same as the no-coolant and the low coolant mass flow-rate data.

The composite plot of coincident heat flux and pressure data at the equivalent shock location of  $y = 0.0$  shows the effect of coolant delivery pressure (mass flow rate). Matching the post-shock pressure ( $p_c/p_e = 2.0$ ) instead of the preshock pressure ( $p_c/p_e = 1.0$ ) doubles the coolant mass flow rate but results in only a small decrease in heat flux. This diminishing return on heat-flux reduction, as shown in the section "Coolant Mass Flow Effects," suggests that multiple small slots would be a more effective arrangement for injecting a given mass flow rate of coolant gas. Also, multiple coolant slots in the presence of swept shocks aid in renewing the coolant layer downstream of the shock interaction and reduce the effect of three-dimensional flow effects.

## Concluding Remarks

An experimental test program for film cooling was conducted in the Calspan 48-Inch Shock Tunnel at a free-stream Mach number of 6.4. Hydrogen was the primary coolant gas, although some helium tests were conducted. To preclude combustion effects, the test stream was nitrogen. Test configurations included coolant mass flow rate effects in undisturbed flow over a flat plate with a rearward-facing coolant injection slot, incident shock interactions, and swept-shock interactions.

Coolant mass flow rate tests show both hydrogen and helium coolant gases to be effective in reducing wall heat flux in undisturbed flow. Hydrogen was a more effective coolant than helium. However, there was a diminishing return on heat-flux reduction with increasing mass flow rate. The basic film-cooling correlation that appears in the literature and utilizes a coolant to free-stream mass flux ratio, was modified to a coolant to free-stream energy flux ratio. The modified correlation collapses the data from both coolant gases into a single curve.



Incident oblique shock interaction tests showed that hydrogen film-cooling effectiveness was essentially destroyed by an incident shock. The region between the slot and the shock was well cooled, but downstream of the shock interaction the heat flux was nearly the same as with no-coolant flow.

Swept-shock interaction tests also showed that the region between the slot and the shock was well cooled; downstream of the shock interaction, however, the heat flux was nearly the same as with no-coolant flow. However, for shocks with equal pressure rises, the swept shock produced larger interaction regions with higher heat fluxes than did incident shocks. These higher heat fluxes are attributed to the three-dimensional growth of the resulting separated flow region and spiral vortex associated with swept shocks.

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Table I. Test Matrix

[Baseline conditions:  $Q_0(\text{ref}) = 61.36 \text{ Btu-ft}^2/\text{sec}$ ;  $p_0(\text{ref}) = 2252 \text{ psia}$ ]

| Configuration     | Run | Coolant        |           | Reynolds number     | Shock interaction |               | Normalization factors |                       |
|-------------------|-----|----------------|-----------|---------------------|-------------------|---------------|-----------------------|-----------------------|
|                   |     | Type           | $p_c/p_e$ |                     | Type              | Location, in. | $Q_0/Q_0(\text{ref})$ | $p_0/p_0(\text{ref})$ |
| Baseline          | 9   | None           |           | $19.8 \times 10^6$  | None              |               | 1                     | 1                     |
| Coolant mass flow | 10  | H <sub>2</sub> | 0.50      | $19.8 \times 10^6$  | None              |               | 0.996                 | 1.025                 |
|                   | 11  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | None              |               | 1.001                 | 1.042                 |
|                   | 12  | H <sub>2</sub> | 1.50      | $19.8 \times 10^6$  | None              |               | 0.993                 | 1.042                 |
|                   | 13  | H <sub>2</sub> | 2.00      | $19.8 \times 10^6$  | None              |               | 0.986                 | 1.021                 |
|                   | 8   | He             | 0.50      | $19.8 \times 10^6$  | None              |               | 1.021                 | 1.028                 |
|                   | 7   | He             | 1.00      | $19.8 \times 10^6$  | None              |               | 0.992                 | 1.001                 |
|                   | 6   | He             | 1.50      | $19.8 \times 10^6$  | None              |               | 1.081                 | 1.080                 |
|                   | 5   | He             | 2.00      | $19.8 \times 10^6$  | None              |               | 1.028                 | 1.035                 |
| Incident shock    | 21  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 2.5° incident     | $x = 2.0$     | 1.044                 | 1.114                 |
|                   | 17  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 5.0° incident     | $x = 2.8$     | 0.995                 | 1.058                 |
|                   | 19  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 7.5° incident     | $x = 2.0$     | 1.054                 | 1.058                 |
|                   | 23  | H <sub>2</sub> | 1.00      | $11.75 \times 10^6$ | 2.5° incident     | $x = 2.0$     | 1.050                 | 1.066                 |
|                   | 24  | H <sub>2</sub> | 1.00      | $11.75 \times 10^6$ | 5.0° incident     | $x = 2.0$     | 1.065                 | 1.107                 |
| Swept shock       | 33  | None           |           | $19.8 \times 10^6$  | 5.0° swept        | $y = -0.424$  | 0.989                 | 1.054                 |
|                   | 35  | None           |           | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.0$     | 0.978                 | 1.058                 |
|                   | 36  | None           |           | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.424$   | 1.008                 | 1.076                 |
|                   | 37  | None           |           | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.848$   | 1.018                 | 1.079                 |
|                   | 32  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = -0.424$  | 1                     | 1.058                 |
|                   | 29  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.0$     | 1.037                 | 1.085                 |
|                   | 25  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.424$   | 1.056                 | 1.076                 |
|                   | 28  | H <sub>2</sub> | 1.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.848$   | 1.033                 | 1.082                 |
|                   | 31  | H <sub>2</sub> | 2.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = -0.424$  | 1.025                 | 1.060                 |
|                   | 30  | H <sub>2</sub> | 2.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.0$     | 1.027                 | 1.054                 |
|                   | 26  | H <sub>2</sub> | 2.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.424$   | 1.027                 | 1.031                 |
|                   | 27  | H <sub>2</sub> | 2.00      | $19.8 \times 10^6$  | 5.0° swept        | $y = 0.848$   | 1.041                 | 1.074                 |

Table II. Free Stream and Coolant Flow Conditions

| Flow variable                      | Free stream<br>(at coolant slot)      | Coolant (at slot exit)    |                           |
|------------------------------------|---------------------------------------|---------------------------|---------------------------|
|                                    |                                       | Hydrogen                  | Helium                    |
| $M$ .....                          | 6.4                                   | 2.7                       | 3                         |
| $R$ .....                          | $11.75 \text{ and } 19.8 \times 10^6$ | 293*                      | 369*                      |
| $\delta$ , in.....                 | 0.34 and 0.44                         | 0.024                     | 0.019                     |
| $p$ , psia .....                   | 0.93                                  | 0.046 to 1.86             | 0.046 to 1.86             |
| $T_0$ , °R.....                    | 2189                                  | 536                       | 536                       |
| $T$ , °R.....                      | 253.5                                 | 218                       | 134                       |
| $V$ , ft/sec .....                 | 5000                                  | 7410                      | 5000                      |
| $m$ , lbm/sec-in <sup>2</sup> .... | 0.344                                 | 0.163 ( $p_c/p_e = 0.5$ ) | 0.520 ( $p_c/p_e = 0.5$ ) |
|                                    |                                       | 0.260 ( $p_c/p_e = 1.0$ ) | 0.749 ( $p_c/p_e = 1.0$ ) |
|                                    |                                       | 0.460 ( $p_c/p_e = 1.5$ ) | 1.170 ( $p_c/p_e = 1.5$ ) |
|                                    |                                       | 0.662 ( $p_c/p_e = 2.0$ ) | 1.580 ( $p_c/p_e = 2.0$ ) |

\*Based on momentum integral thickness.

Table III. Free Stream and Coolant Gas Properties

| Property                           | Free-stream<br>nitrogen,<br>$T = 253.5^\circ\text{R}$ | Coolant gas                          |                                    |
|------------------------------------|---|--------------------------------------|------------------------------------|
|                                    |   | Hydrogen,<br>$T = 218^\circ\text{R}$ | Helium,<br>$T = 134^\circ\text{R}$ |
| $\gamma^*$ .....                   | 1.4   | 1.4                                  | 1.67                               |
| Gas constant, ft-lbf/lbm-°R.....   | 55.16   | 766.5                                | 386.1                              |
| $c_v$ , Btu/lbm-°R.....            | 0.18  | 2.46                                 | 0.74                               |
| $\mu$ , lbm/ft-sec .....           | $0.63 \times 10^{-5}$                                 | $0.38 \times 10^{-5}$                | $1.07 \times 10^{-5}$              |
| $\nu$ , ft <sup>2</sup> /sec ..... | $4.53 \times 10^{-5}$                                 | $67 \times 10^{-5}$                  | $72 \times 10^{-5}$                |

\*Assumed constant with temperature.

Table IV. Coolant Mass Flow Effects for Heat-Flux Data

| Gauge<br>label | Distance<br>from<br>slot, in. | Heat flux, Btu/ft <sup>2</sup> -sec |                  |                 |                 |                 |                 |                 |                 |                 |
|----------------|-------------------------------|-------------------------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                |                               | No<br>coolant                       | Hydrogen coolant |                 |                 |                 | Helium coolant  |                 |                 |                 |
|                |                               |                                     | $p_c/p_e = 0.5$  | $p_c/p_e = 1.0$ | $p_c/p_e = 1.5$ | $p_c/p_e = 2.0$ | $p_c/p_e = 0.5$ | $p_c/p_e = 1.0$ | $p_c/p_e = 1.5$ | $p_c/p_e = 2.0$ |
| P5H1           | 0.41                          | 0.00                                | 0.05             | -0.31           | -0.25           | 0.25            | -0.78           | -0.17           | -0.61           | -0.17           |
| P5H2           | 0.50                          | 3.33                                | 0.20             | 0.93            | -0.13           | 0.66            | -0.12           | 1.43            | -0.61           | 1.43            |
| P5H3           | 0.60                          | 7.77                                | 0.49             | 0.55            | -0.94           | 0.27            | 1.13            | 3.13            | -0.30           | 3.13            |
| P5H4           | 0.70                          | 11.75                               | -0.01            | 0.25            | -0.12           | 0.50            | 0.79            | 0.47            | 0.02            | 0.47            |
| P5H5           | 0.80                          |                                     |                  |                 |                 |                 | 1.52            | 1.26            | 0.20            | 1.26            |
| P5H6           | 0.89                          | 10.90                               | -0.67            | 0.38            | 0.59            | 0.71            | -0.26           | 1.69            | -0.28           | 1.69            |
| P5H7           | 0.99                          | 10.55                               | -1.85            | 0.78            | -0.49           | 0.52            | -0.50           | -0.68           | -0.93           | -0.68           |
| P5H8           | 1.09                          | 10.49                               | -1.23            | 0.24            | 0.59            | 1.59            | 0.18            | 0.58            | 0.01            | 0.58            |
| P5H9           | 1.17                          | 10.64                               | -2.22            | -1.19           | -0.47           | -0.18           | -0.75           | 0.50            | -1.38           | 0.50            |
| P5H10          | 1.26                          | 8.59                                | -1.90            | -1.93           | 0.10            | 0.06            | 0.57            | 0.63            | 0.90            | 0.63            |
| P5H11          | 1.35                          | 8.54                                | -1.75            | -1.39           | -0.40           | 0.14            | -0.03           | 1.78            | 0.84            | 1.78            |
| P5H12          | 1.40                          |                                     |                  |                 |                 |                 | -0.38           | 2.16            | 0.73            | 2.16            |
| P5H13          | 1.48                          | 8.85                                | -0.64            | 0.68            | -0.31           | 1.86            | -0.70           | 1.82            | 0.09            | 1.82            |
| P5H15          | 1.67                          | 8.43                                | -0.32            | 0.56            | -0.17           | 0.68            | -0.20           | 0.98            | 0.81            | 0.98            |
| P5H16          | 1.76                          | 8.07                                | 0.75             | 0.00            | 0.38            | 0.95            | -0.35           | 2.34            | 0.50            | 2.34            |
| P5H17          | 1.86                          | 9.03                                | 0.84             | -0.22           | 0.40            | 0.92            | -1.78           | 2.29            | 0.59            | 2.29            |
| P5H21          | 2.25                          |                                     |                  |                 |                 |                 | 0.36            | 3.25            | 0.88            | 3.25            |
| P5H23          | 2.47                          | 8.92                                | 1.14             | 0.34            | 0.18            | 0.58            | 0.47            | 1.24            | 0.32            | 1.24            |
| P5H24          | 2.57                          | 8.70                                | 0.97             | 0.21            | 0.05            | 0.40            | 0.32            | 1.45            | 0.26            | 1.45            |
| P5H25          | 2.67                          | 8.77                                | 1.27             | 0.67            | 0.37            | 0.94            | 0.82            | 1.47            | 0.48            | 1.47            |
| P5H26          | 2.76                          | 8.78                                | 1.69             | 1.01            | 0.70            | 1.15            | 0.94            | 1.59            | 0.43            | 1.59            |
| P5H27          | 2.86                          | 8.19                                | 1.14             | 0.58            | 0.00            | 0.38            | 0.53            | 1.04            | 0.29            | 1.04            |
| P5H28          | 2.96                          | 9.11                                | 1.52             | 0.84            | 0.44            | 0.83            | 0.97            | 1.51            | 0.37            | 1.51            |
| P5H29          | 3.05                          | 8.41                                | 1.32             | 0.79            | 0.16            | 0.67            | 0.82            | 1.37            | 0.37            | 1.37            |
| P5H30          | 3.15                          | 8.76                                | 1.47             | 0.64            | 0.11            | 0.48            | 0.94            | 1.45            | 0.31            | 1.45            |
| P5H31          | 3.25                          | 9.00                                | 1.50             | 0.96            | 0.22            | 0.58            | 0.71            | 1.94            | 0.44            | 1.94            |
| P5H32          | 3.34                          | 8.36                                | 1.25             | 0.42            | 0.19            | 0.31            | 0.97            | 1.42            | 0.44            | 1.42            |
| P5H33          | 3.49                          | 8.20                                | 1.67             | 0.91            | 0.54            | 0.58            | 1.31            | 1.89            | 0.67            | 1.89            |
| P5H34          | 3.69                          | 7.79                                | 1.41             | 0.72            | 0.30            | 0.53            | 0.47            | 0.93            | 0.38            | 0.93            |
| P5H35          | 3.90                          | 7.71                                | 1.59             | 1.00            | -0.06           | 0.51            | 0.30            | 1.11            | 0.48            | 1.11            |
| P5H36          | 4.10                          | 7.89                                | 1.96             | 0.88            | 0.74            | 0.94            | 1.52            | 0.08            | 0.66            | 0.08            |
| P5H37          | 4.31                          | 8.11                                | 1.78             | 1.21            | 0.10            | 0.65            | 0.90            | 1.05            | 0.75            | 1.05            |
| P5H40          | 4.96                          | 8.15                                | 1.97             | 1.38            | 0.76            | 0.56            | 1.49            | 0.86            | 0.51            | 0.86            |
| P5H41          | 5.16                          | 8.18                                | 1.90             | 1.57            | 0.70            | 0.51            | 1.24            | 1.16            | 0.52            | 1.16            |
| P12H1          | 5.48                          | 8.53                                | 2.89             | 2.44            | 0.98            | 1.09            | 1.44            | 1.61            | 0.55            | 1.61            |
| P12H2          | 5.58                          | 8.46                                | 2.70             | 2.50            | 0.73            | 0.71            | 1.44            | 1.45            | 0.60            | 1.45            |
| P12H3          | 5.67                          | 7.87                                | 2.64             | 1.90            | 1.42            | 0.67            | 1.86            | 1.52            | 1.32            | 1.52            |
| P12H4          | 5.77                          | 9.06                                | 2.99             | 2.47            | 2.32            | 1.20            | 2.13            | 2.14            | 2.12            | 2.14            |
| P12H6          | 5.97                          | 8.24                                | 3.14             | 2.11            | 1.28            | 0.81            | 2.08            | 1.54            | 1.02            | 1.54            |
| P12H7          | 6.07                          | 7.55                                | 2.77             | 1.61            | 1.23            | 0.91            | 2.14            | 0.91            | 0.91            | 0.91            |
| P12H9          | 6.26                          | 7.70                                | 2.33             | 1.73            | 0.82            | 0.58            | 1.88            | 1.18            | 0.91            | 1.18            |
| P12H11         | 6.46                          | 7.42                                | 2.62             | 2.25            | 1.00            | 1.06            |                 | 1.61            | 1.32            | 1.61            |
| P12H13         | 6.64                          | 7.32                                | 2.90             | 1.93            | 1.20            | 1.27            | 1.84            | 2.03            | 1.36            | 2.03            |
| P12H15         | 6.81                          | 7.33                                | 3.02             | 2.99            | 1.60            | 0.41            | 2.79            | 2.38            | 1.20            | 2.38            |
| P12H17         | 6.99                          | 7.67                                | 2.94             | 2.26            | 1.32            | 0.86            | 2.78            | 2.24            | 1.56            | 2.24            |
| P12H19         | 7.17                          | 8.00                                | 2.81             | 2.08            | 1.06            | 0.80            | 2.38            | 1.88            | 1.26            | 1.88            |
| P12H21         | 7.63                          | 7.74                                | 3.02             | 1.97            | 1.10            | 0.80            | 1.68            | 0.96            | 0.84            | 0.96            |
| P12H23         | 8.90                          | 7.98                                | 3.60             | 2.48            | 1.57            | 1.17            | 2.17            | 1.24            | 1.12            | 1.24            |
| P12H27         | 11.46                         | 8.69                                | 3.94             | 2.31            | 1.35            | 1.33            |                 | 1.28            | 0.71            | 1.28            |
| P12H29         | 12.74                         | 7.00                                | 4.12             | 2.73            | 1.70            | 1.54            | 2.71            | 1.36            | 1.37            | 1.36            |
| P12H30         | 13.38                         | 8.56                                | 4.89             | 3.21            | 2.20            | 1.63            | 3.28            | 1.61            | 1.59            | 1.61            |
| P12H31         | 14.02                         | 8.53                                | 5.17             | 3.33            | 2.31            | 1.99            | 3.33            | 1.81            | 1.73            | 1.81            |
| P12H32         | 14.66                         | 8.02                                | 4.93             | 3.41            | 2.06            | 1.81            | 3.75            | 1.87            | 1.97            | 1.87            |
| P12H33         | 15.31                         | 8.59                                | 5.20             | 3.49            | 2.30            | 1.92            | 3.69            | 1.75            | 1.75            | 1.75            |
| P12H34         | 15.95                         | 8.28                                | 5.60             | 3.74            | 2.43            | 2.10            | 3.80            | 1.84            | 1.85            | 1.84            |
| P12H35         | 16.58                         | 8.11                                | 5.61             | 3.66            | 2.48            | 2.15            | 3.81            | 1.80            | 1.94            | 1.80            |

Table V. Coolant Mass Flow Effects for Pressure Distribution Data

| Gauge label | Distance from slot, in. | Pressure, psia |                  |                 |                 |                 |                 |                 |                 |                 |
|-------------|-------------------------|----------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|             |                         | No coolant     | Hydrogen coolant |                 |                 |                 | Helium coolant  |                 |                 |                 |
|             |                         |                | $p_c/p_e = 0.5$  | $p_c/p_e = 1.0$ | $p_c/p_e = 1.5$ | $p_c/p_e = 2.0$ | $p_c/p_e = 0.5$ | $p_c/p_e = 1.0$ | $p_c/p_e = 1.5$ | $p_c/p_e = 2.0$ |
| P5P10       | 0.64                    | 0.30           | 0.67             | 0.84            | 0.83            | 1.09            | 1.00            | 0.94            | 1.00            |                 |
| P5P1        | 0.73                    | 0.58           | 0.73             | 0.80            | 0.87            | 0.76            | 0.80            | 0.86            | 0.72            | 0.68            |
| P5P12       | 1.15                    | 0.70           | 0.91             | 0.94            | 1.03            | 1.02            | 0.92            | 0.96            | 0.95            | 0.93            |
| P5P2        | 1.25                    | 0.86           | 1.09             | 1.12            | 1.16            | 1.25            | 1.01            | 1.06            | 1.06            | 1.08            |
| P5P14       | 1.62                    | 0.71           | 0.91             | 0.94            | 1.00            | 1.04            | 0.90            | 0.95            | 0.96            | 1.03            |
| P5P3        | 1.76                    | 0.83           | 1.00             | 1.04            | 1.06            | 1.09            | 1.01            | 1.04            | 1.03            | 1.13            |
| P5P16       | 2.18                    | 0.81           | 0.97             | 1.01            | 1.06            | 1.09            | 1.00            | 1.04            | 1.03            | 1.12            |
| P5P4        | 2.26                    | 0.85           | 0.98             | 1.03            | 1.07            | 1.10            | 1.00            | 1.04            | 1.02            | 1.07            |
| P5P5        | 2.77                    | 0.85           | 0.98             | 1.03            | 1.07            | 1.10            | 1.01            | 1.05            | 1.03            | 1.08            |
| P5P6        | 3.27                    | 0.85           | 1.05             | 1.07            | 1.14            | 1.16            | 1.06            | 1.10            | 1.06            | 1.13            |
| P5P8        | 4.27                    | 0.97           | 1.13             | 1.15            | 1.21            | 1.24            | 1.14            | 1.17            | 1.14            | 1.22            |
| P5P9        | 4.77                    | 0.82           | 0.98             | 0.98            | 1.03            | 1.04            | 0.93            | 0.99            | 0.99            | 1.04            |
| P12P1       | 5.72                    | 0.92           | 0.96             | 1.00            | 1.05            | 1.03            | 0.97            | 1.03            | 1.00            | 1.03            |
| P12P5       | 8.28                    | 0.89           | 0.76             | 0.98            | 1.02            | 1.03            | 0.98            | 1.03            | 1.00            | 1.01            |
| P12P7       | 9.56                    | 0.93           | 0.94             | 0.98            | 0.98            | 0.99            | 0.98            | 1.03            | 0.94            | 0.98            |
| P12P8       | 10.20                   | 0.88           | 0.88             | 0.90            | 0.94            | 0.94            | 0.90            | 0.94            | 0.91            | 0.94            |
| P12P9       | 10.84                   | 0.82           | 0.90             | 0.92            | 0.96            | 0.96            | 0.88            | 0.93            | 0.90            | 0.92            |
| P12P10      | 11.48                   | 0.85           | 0.85             | 0.88            | 0.91            | 0.91            | 0.88            | 0.90            | 0.89            | 0.91            |
| P12P11      | 12.12                   | 0.88           | 0.89             | 0.89            | 0.92            | 0.92            | 0.91            | 0.93            | 0.90            | 0.92            |
| P12P12      | 12.76                   | 1.03           | 1.03             | 1.05            | 1.08            | 1.07            | 1.07            | 1.07            | 1.04            | 1.08            |
| P12P13      | 13.40                   | 1.07           | 1.06             | 1.10            | 1.13            | 1.12            | 1.10            | 1.09            | 1.07            | 1.11            |
| P12P14      | 14.04                   | 0.88           | 0.87             | 0.89            | 0.92            | 0.92            | 0.90            | 0.93            | 0.91            | 0.93            |
| P12P15      | 14.68                   | 0.87           | 0.86             | 0.87            | 0.89            | 0.89            | 0.87            | 0.90            | 0.88            | 0.90            |
| P12P16      | 15.32                   | 0.91           | 0.87             | 0.90            | 0.93            | 0.92            | 0.88            | 0.92            | 0.89            | 0.93            |
| P12P17      | 15.96                   | 0.91           | 0.92             | 0.93            | 0.95            | 0.94            | 0.93            | 0.96            | 0.92            | 0.95            |

Table VI. Incident-Shock Heat-Flux Data With Hydrogen Coolant at  $m = 0.260$  ( $p_c/p_e = 1.0$ )

| Gauge label | Distance from slot, in. | Heat flux, Btu/ft <sup>2</sup> -sec |            |            |            |                         |            |
|-------------|-------------------------|-------------------------------------|------------|------------|------------|-------------------------|------------|
|             |                         | $R = 19.8 \times 10^6$              |            |            |            | $R = 11.75 \times 10^6$ |            |
|             |                         | No shock                            | 2.5° shock | 5.0° shock | 7.5° shock | 2.5° shock              | 5.0° shock |
| P5H1        | 0.41                    | -0.31                               | -0.18      | 1.36       | 0.93       | 0.74                    | 0.90       |
| P5H2        | 0.5                     | 0.93                                | -0.10      | 0.75       | -0.84      | -0.60                   | 0.48       |
| P5H3        | 0.6                     | 0.55                                | -0.67      | 1.98       | -0.34      | -0.23                   | 0.72       |
| P5H4        | 0.7                     | 0.25                                | 0.20       | -0.16      | -1.12      | -0.74                   | -2.56      |
| P5H6        | 0.89                    | 0.38                                | -0.18      | -0.14      | -0.13      | -0.95                   | -0.92      |
| P5H7        | 0.99                    | 0.78                                | -0.12      | -2.31      | 0.65       | 2.48                    | -1.59      |
| P5H8        | 1.09                    | 0.24                                | -0.71      | -0.61      | -0.18      | -4.88                   | -2.94      |
| P5H9        | 1.17                    | -1.19                               | 0.50       | -0.78      | -0.12      | 0.53                    | -0.48      |
| P5H10       | 1.26                    | -1.93                               | -2.30      | -0.97      | -1.17      | -1.46                   | -0.51      |
| P5H11       | 1.35                    | -1.39                               | -1.85      | -1.93      | -1.62      | -0.59                   | -1.43      |
| P5H13       | 1.48                    | 0.68                                | -0.26      | -2.55      | 0.77       | -1.15                   | -1.10      |
| P5H15       | 1.67                    | 0.56                                | -2.08      | -1.00      | -2.39      | -0.04                   | 0.05       |
| P5H16       | 1.76                    | 0.00                                | -0.96      | -0.56      | -0.40      | -0.31                   | -0.49      |
| P5H17       | 1.86                    | -0.22                               | 1.44       | -2.54      | 2.57       | -0.73                   | -2.44      |
| P5H24       | 2.57                    | 0.21                                | 0.14       | 0.64       | 3.47       | 0.39                    | 1.55       |
| P5H25       | 2.67                    | 0.67                                | 0.54       | 0.52       | 3.12       | 0.51                    | 2.54       |
| P5H26       | 2.76                    | 1.01                                | 0.95       | 0.00       | 3.13       | 0.55                    | 2.37       |
| P5H27       | 2.86                    | 0.58                                | 1.21       | 0.46       | 3.09       | 1.19                    | 2.10       |
| P5H28       | 2.96                    | 0.84                                | 1.24       | 0.87       | 3.60       | 2.40                    | 2.78       |
| P5H29       | 3.05                    | 0.79                                | 1.53       | 0.56       | 3.55       | 1.70                    | 2.96       |
| P5H30       | 3.15                    | 0.64                                | 1.66       | 1.03       | 4.15       | 2.04                    | 3.33       |
| P5H31       | 3.25                    | 0.96                                | 1.89       | 0.95       | 4.15       | 2.33                    | 4.05       |
| P5H33       | 3.49                    | 0.91                                | 1.29       | 0.81       | 4.51       | 2.68                    | 4.93       |
| P5H34       | 3.69                    | 0.72                                | 1.67       | 3.14       | 6.65       | 4.13                    | 5.72       |
| P5H35       | 3.9                     | 1.00                                | 2.15       | 3.93       | 8.22       | 2.51                    | 6.39       |
| P5H36       | 4.1                     | 0.88                                | 2.52       | 4.05       | 9.62       | 2.80                    | 6.09       |
| P5H37       | 4.31                    | 1.21                                | 2.67       | 6.26       | 12.97      |                         |            |
| P5H40       | 4.96                    | 1.38                                | 2.98       | 8.34       | 20.04      | 5.57                    | 9.80       |
| P5H41       | 5.16                    | 1.57                                | 3.37       | 8.12       | 22.21      | 5.55                    | 11.51      |
| P12H1       | 5.48                    | 2.44                                | 5.06       | 10.35      | 29.56      | 8.62                    | 18.24      |
| P12H2       | 5.58                    | 2.50                                | 5.64       | 10.85      | 29.78      | 7.77                    | 17.69      |
| P12H3       | 5.67                    | 1.90                                | 5.62       | 9.54       | 27.77      | 7.02                    | 16.59      |
| P12H4       | 5.77                    | 2.47                                | 6.45       | 11.44      | 30.22      | 7.53                    | 17.41      |
| P12H6       | 5.97                    | 2.11                                | 5.35       | 11.74      | 30.42      | 7.44                    | 16.66      |
| P12H7       | 6.07                    | 1.61                                | 4.69       | 12.94      | 31.54      | 6.33                    | 18.49      |
| P12H9       | 6.26                    | 1.73                                | 5.51       | 12.84      | 33.03      | 6.71                    | 17.94      |
| P12H11      | 6.46                    | 2.25                                | 6.48       | 13.23      | 36.49      | 7.91                    | 20.30      |
| P12H13      | 6.64                    | 1.93                                | 6.58       | 14.53      | 37.12      | 8.07                    | 21.37      |
| P12H17      | 6.99                    | 2.26                                | 6.84       | 16.52      | 40.31      | 6.38                    | 21.35      |
| P12H19      | 7.17                    | 2.08                                | 4.24       | 17.41      | 44.46      | 5.49                    | 16.09      |
| P12H21      | 7.63                    | 1.97                                | 7.66       | 17.51      | 46.95      | 3.37                    | 15.79      |
| P12H23      | 8.9                     | 2.48                                | 9.67       | 27.46      | 57.40      | 10.60                   | 30.13      |
| P12H27      | 11.46                   | 2.31                                | 12.01      | 29.55      | 55.61      | 11.07                   | 32.13      |
| P12H29      | 12.74                   | 2.73                                | 11.80      | 30.15      | 50.63      | 12.10                   | 28.03      |
| P12H30      | 13.38                   | 3.21                                | 13.99      | 34.63      | 57.00      | 13.93                   | 30.66      |
| P12H31      | 14.02                   | 3.33                                | 14.41      | 34.13      | 55.65      | 14.01                   | 30.31      |
| P12H32      | 14.66                   | 3.41                                | 15.35      | 34.13      | 49.65      | 14.37                   | 30.15      |
| P12H33      | 15.31                   | 3.49                                | 15.14      | 34.03      | 44.24      | 15.74                   | 31.65      |
| P12H34      | 15.95                   | 3.74                                | 15.24      | 34.23      | 37.38      | 15.47                   | 28.74      |
| P12H35      | 16.58                   | 3.66                                | 16.50      | 32.04      | 32.41      | 15.64                   | 25.27      |

Table VII. Incident-Shock Pressure Distribution Data With Hydrogen Coolant at  $m = 0.260$  ( $p_c/p_e = 1.0$ )

| Gauge label | Distance from slot, in. | Pressure, psia         |            |            |            |                         |            |
|-------------|-------------------------|------------------------|------------|------------|------------|-------------------------|------------|
|             |                         | $R = 19.8 \times 10^6$ |            |            |            | $R = 11.75 \times 10^6$ |            |
|             |                         | No shock               | 2.5° shock | 5.0° shock | 7.5° shock | 2.5° shock              | 5.0° shock |
| P5P10       | 0.64                    | 0.84                   | 0.81       | 0.79       | 0.80       | 0.72                    | 0.76       |
| P5P1        | 0.73                    | 0.80                   | 0.95       | 0.83       | 0.88       | 0.74                    | 0.78       |
| P5P12       | 1.15                    | 0.94                   | 0.62       | 0.97       | 0.93       | 0.90                    | 0.92       |
| P5P2        | 1.25                    | 1.12                   | 1.11       | 1.06       | 1.08       | 1.01                    | 1.05       |
| P5P14       | 1.62                    | 0.94                   | 0.95       | 0.93       | 0.95       | 0.88                    | 0.91       |
| P5P3        | 1.76                    | 1.04                   | 0.94       | 1.06       | 1.08       | 1.01                    | 1.03       |
| P5P16       | 2.18                    | 1.01                   | 1.11       | 1.02       | 1.37       | 0.99                    | 1.04       |
| P5P4        | 2.26                    | 1.03                   | 1.35       | 1.07       | 1.88       | 1.06                    | 1.09       |
| P5P5        | 2.77                    | 1.03                   | 1.69       | 1.05       | 2.44       | 1.33                    | 1.89       |
| P5P6        | 3.27                    | 1.07                   | 1.82       | 1.02       | 2.61       | 1.85                    | 2.55       |
| P5P8        | 4.27                    | 1.16                   | 2.32       | 2.91       | 4.28       | 2.55                    | 4.00       |
| P5P9        | 4.77                    | 0.98                   | 1.80       | 2.79       | 4.08       | 2.35                    | 3.61       |
| P12P1       | 5.72                    | 1.00                   | 2.29       | 3.57       | 5.69       | 2.75                    | 4.20       |
| P12P3       | 7.00                    | 0.99                   | 2.16       | 4.14       | 7.22       | 2.40                    | 4.79       |
| P12P5       | 8.28                    | 0.98                   | 1.62       | 4.54       | 7.86       | 2.33                    | 4.76       |
| P12P7       | 9.56                    | 0.98                   | 2.37       | 4.94       | 8.49       | 2.18                    | 4.40       |
| P12P8       | 10.20                   | 0.90                   | 1.87       | 4.43       | 8.02       | 2.07                    | 4.35       |
| P12P9       | 10.84                   | 0.92                   | 2.27       | 4.70       | 8.09       | 1.96                    | 3.82       |
| P12P10      | 11.48                   | 0.88                   | 2.33       | 4.42       | 7.89       | 2.07                    | 4.17       |
| P12P11      | 12.12                   | 0.90                   | 2.15       | 4.57       | 7.95       | 2.05                    | 4.03       |
| P12P12      | 12.76                   | 1.05                   | 2.64       | 5.06       | 8.34       | 2.25                    | 4.52       |
| P12P13      | 13.40                   | 1.09                   | 2.80       | 5.04       | 7.99       | 2.37                    | 4.53       |
| P12P14      | 14.04                   | 0.89                   | 2.34       | 4.45       | 7.47       | 2.04                    | 3.99       |
| P12P15      | 14.68                   | 0.87                   | 2.24       | 4.33       | 6.60       | 1.99                    | 3.88       |
| P12P16      | 15.32                   | 0.90                   | 2.37       | 4.45       | 5.80       | 2.09                    | 4.00       |
| P12P17      | 15.96                   | 0.93                   | 2.38       | 4.32       | 4.67       | 2.15                    | 3.92       |

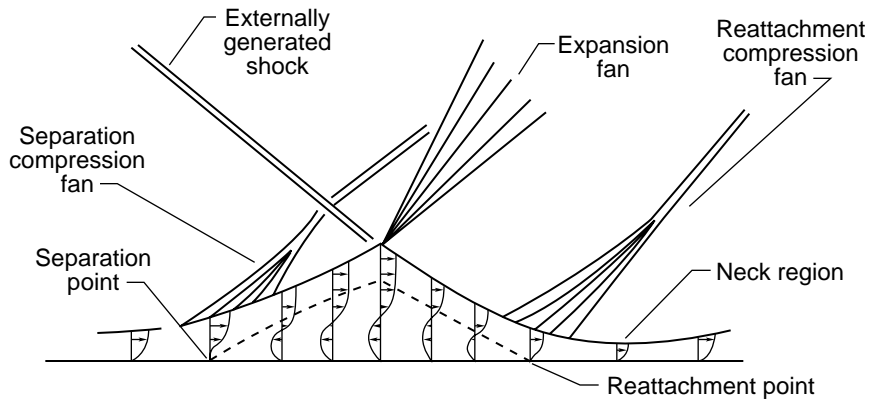
Table VIII. Swept-Shock Heat-Flux Data

| Gauge<br>label | Distance<br>from<br>slot, in. | Heat flux, Btu/ft <sup>2</sup> -sec |        |        |        |                                 |        |        |        |                                 |        |        |        |
|----------------|-------------------------------|-------------------------------------|--------|--------|--------|---------------------------------|--------|--------|--------|---------------------------------|--------|--------|--------|
|                |                               | No coolant                          |        |        |        | $m = 0.260$ ( $p_c/p_e = 1.0$ ) |        |        |        | $m = 0.662$ ( $p_c/p_e = 2.0$ ) |        |        |        |
|                |                               | Pos. 1                              | Pos. 2 | Pos. 3 | Pos. 4 | Pos. 1                          | Pos. 2 | Pos. 3 | Pos. 4 | Pos. 1                          | Pos. 2 | Pos. 3 | Pos. 4 |
| P5H1           | 0.41                          |                                     |        |        |        | -1.49                           | -0.31  | 0.69   | 0.77   | 0.79                            | -2.34  | 0.84   | 0.69   |
| P5H2           | 0.50                          |                                     |        |        |        | -1.11                           | 0.14   | -6.00  | 0.30   | 3.36                            | -1.37  | -0.13  | 0.84   |
| P5H3           | 0.60                          | 8.36                                | 9.98   | 10.38  | 9.80   | -0.73                           | 1.11   | -4.30  | 3.32   | 5.93                            | 3.46   | -0.52  | 1.60   |
| P5H4           | 0.70                          | 18.42                               | 13.69  | 14.62  | 13.64  | 2.86                            | 0.34   | -8.65  | -3.46  | -1.68                           | 0.56   | 1.30   | 0.75   |
| P5H5           | 0.80                          | 18.94                               | 11.34  | 14.92  | 12.42  | -0.33                           | 0.57   | -8.81  | -0.30  | -2.58                           | 2.77   | -0.47  | -0.26  |
| P5H6           | 0.89                          | 14.52                               | 11.15  | 10.18  | 8.31   | -0.23                           | -1.44  | -8.56  | 0.07   | 1.82                            | -2.98  | 1.22   | 0.16   |
| P5H7           | 0.99                          | 11.78                               | 12.91  | 11.89  | 9.26   | 0.87                            | -1.14  | -7.85  | -3.62  | 5.23                            | 0.05   | -0.29  | -0.51  |
| P5H8           | 1.09                          | 12.56                               | 11.54  | 10.89  | 9.21   | 0.10                            | -1.28  | -3.22  | -0.82  | -1.10                           | -0.45  | -1.73  | 0.66   |
| P5H10          | 1.26                          | 10.25                               | 10.66  | 10.89  | 8.45   | -0.72                           | -1.53  | -2.45  | -1.46  | 1.80                            | 2.63   | -0.69  | 0.86   |
| P5H13          | 1.48                          | 14.38                               | 13.01  | 10.28  | 8.52   | 0.01                            | 0.14   | 1.59   | -0.59  | -1.06                           | 0.74   | -1.54  | -0.80  |
| P5H15          | 1.67                          | 10.68                               | 11.34  | 10.06  | 9.44   | -0.30                           | -0.56  | 3.09   | -1.98  | 5.03                            | 2.41   | 2.19   | 0.13   |
| P5H16          | 1.76                          |                                     |        |        |        | -1.53                           | -0.52  | 2.84   | -0.29  | 0.36                            | -1.65  | -1.70  | -0.22  |
| P5H17          | 1.86                          | 13.09                               | 15.75  | 9.69   | 10.28  | -0.55                           | 0.04   | 0.93   | 0.59   | -1.29                           | 2.72   | 0.85   | -1.78  |
| P5H21          | 2.25                          | 14.99                               | 16.23  | 11.10  | 9.65   |                                 |        |        |        |                                 |        |        |        |
| P5H23          | 2.47                          | 17.32                               | 15.75  | 11.89  | 10.12  | 1.65                            | 1.21   | 1.68   | 1.31   | 1.00                            | 0.62   | 0.98   | 0.31   |
| P5H24          | 2.57                          | 17.20                               | 15.65  | 12.10  | 10.28  | 2.07                            | 1.88   | 1.92   | 1.90   | 1.35                            | 1.15   | 1.05   | 0.80   |
| P5H25          | 2.67                          | 17.31                               | 15.55  | 12.20  | 10.28  | 2.31                            | 1.55   | 1.55   | 1.76   | 0.91                            | 0.73   | 0.72   | 0.63   |
| P5H26          | 2.76                          | 17.48                               | 15.45  | 12.40  | 10.49  | 1.79                            | 1.23   | 1.27   | 1.40   | 0.38                            | 0.43   | 0.22   | 0.33   |
| P5H27          | 2.86                          | 16.30                               | 14.18  | 11.39  | 9.75   | 1.81                            | 1.50   | 1.72   | 2.00   | 0.87                            | 0.55   | 0.79   | 0.62   |
| P5H28          | 2.96                          | 18.04                               | 15.65  | 13.00  | 11.20  | 2.25                            | 2.05   | 2.09   | 2.06   | 1.65                            | 0.97   | 1.08   | 0.69   |
| P5H29          | 3.05                          | 16.99                               | 14.47  | 12.10  | 10.14  | 2.36                            | 1.70   | 1.97   | 1.92   | 1.34                            | 0.81   | 1.06   | 0.66   |
| P5H30          | 3.15                          | 17.89                               | 15.26  | 12.70  | 10.49  | 2.42                            | 1.89   | 2.07   | 2.11   | 1.47                            | 1.07   | 1.12   | 0.69   |
| P5H31          | 3.25                          | 17.94                               | 15.55  | 12.60  | 10.55  | 2.80                            | 2.15   | 2.77   | 2.69   | 1.76                            | 1.54   | 1.41   | 1.16   |
| P5H33          | 3.49                          | 17.30                               | 15.26  | 12.50  | 10.69  | 1.98                            | 1.77   | 2.26   | 2.05   | 0.97                            | 1.24   | 0.64   | 1.27   |
| P5H34          | 3.69                          | 17.49                               | 15.16  | 12.70  | 10.49  | 2.79                            | 1.59   | 2.08   | 2.16   | 1.48                            | 1.08   | 0.94   | 1.20   |
| P5H35          | 3.90                          | 16.94                               | 14.87  | 12.30  | 9.28   |                                 |        |        |        |                                 |        |        |        |
| P5H36          | 4.10                          | 17.00                               | 15.06  | 12.90  | 9.69   | 3.20                            | 2.29   | 2.66   | 2.26   | 1.23                            | 1.39   | 0.67   | 0.85   |
| P5H40          | 4.96                          | 19.97                               | 17.51  | 14.31  | 10.79  | 5.58                            | 3.65   | 2.59   | 3.06   | 2.85                            | 2.01   | 1.76   | 1.86   |
| P5H41          | 5.16                          | 20.00                               | 17.51  | 14.31  | 10.59  | 5.83                            | 3.92   | 2.97   | 3.68   | 2.91                            | 2.27   | 2.10   | 2.48   |
| P12H1          | 5.48                          | 29.56                               | 26.80  | 19.86  | 13.84  | 18.48                           | 9.48   | 5.64   | 3.77   | 7.02                            | 3.93   | 2.17   | 2.06   |
| P12H2          | 5.58                          | 33.19                               | 24.25  | 19.25  | 13.74  | 18.40                           | 10.00  | 6.45   | 4.30   | 7.10                            | 4.20   | 2.69   | 2.81   |
| P12H3          | 5.67                          | 29.17                               | 21.91  | 16.93  | 12.73  | 16.59                           | 8.25   | 5.87   | 2.90   | 6.51                            | 3.79   | 1.16   | 2.59   |
| P12H4          | 5.77                          | 28.93                               | 23.67  | 18.35  | 13.84  | 15.71                           | 9.08   | 7.19   | 3.02   | 6.19                            | 5.88   | 2.90   | 2.74   |
| P12H6          | 5.97                          | 24.43                               | 21.32  | 16.03  | 13.54  | 14.68                           | 8.85   | 6.70   | 3.09   | 5.37                            | 6.09   | 2.72   | 2.13   |
| P12H7          | 6.07                          | 24.64                               | 22.20  | 16.83  | 13.13  | 18.06                           | 11.41  | 7.77   | 4.01   | 5.91                            | 5.87   | 3.89   | 2.73   |
| P12H9          | 6.26                          | 21.81                               | 20.34  | 17.54  | 12.52  | 17.34                           | 10.89  | 7.28   | 3.55   | 7.40                            | 5.92   | 4.53   | 2.35   |
| P12H11         | 6.46                          | 21.15                               | 20.05  | 17.74  | 12.62  | 17.82                           | 10.58  | 8.31   | 3.53   | 8.26                            | 6.90   | 4.41   | 2.73   |
| P12H13         | 6.64                          | 21.15                               | 21.12  | 17.04  | 12.62  | 18.90                           | 12.55  | 9.44   | 4.56   | 8.53                            | 6.84   | 5.75   | 2.73   |
| P12H17         | 6.99                          | 21.08                               | 21.71  | 15.83  | 13.64  | 19.15                           | 12.76  | 8.18   | 5.20   | 8.99                            | 7.62   | 2.81   | 1.78   |
| P12H19         | 7.17                          | 22.57                               | 23.57  | 16.83  | 14.76  | 21.07                           | 16.70  | 9.16   | 6.98   | 10.97                           | 8.50   | 5.62   | 3.14   |
| P12H21         | 7.63                          | 23.64                               | 24.94  | 17.54  | 14.66  | 21.36                           | 15.04  | 11.51  | 7.33   |                                 | 9.06   | 4.49   | 2.09   |
| P12H23         | 8.90                          | 23.93                               | 25.33  | 20.26  | 17.71  | 21.64                           | 18.67  | 17.11  | 12.71  | 13.12                           | 11.50  | 9.52   | 3.59   |
| P12H27         | 11.46                         | 19.94                               | 22.30  | 21.97  | 20.16  | 18.97                           | 20.12  | 21.65  | 17.46  |                                 | 15.00  | 14.79  | 9.99   |
| P12H29         | 12.74                         | 16.15                               | 18.29  | 20.97  | 18.93  | 15.62                           | 18.25  | 19.96  | 18.80  | 14.56                           | 17.36  | 17.87  | 13.12  |
| P12H30         | 13.38                         | 18.30                               | 20.24  | 23.99  | 22.60  | 17.53                           | 20.64  | 22.39  | 21.59  | 15.17                           | 19.72  | 21.36  | 15.41  |
| P12H31         | 14.02                         | 16.75                               | 18.68  | 22.98  | 22.50  | 16.42                           | 19.39  | 21.33  | 21.90  | 14.76                           | 19.00  | 20.85  | 16.86  |
| P12H32         | 14.66                         | 16.59                               | 18.58  | 22.68  | 23.31  | 16.34                           | 19.08  | 20.70  | 22.93  | 14.25                           | 17.87  | 20.75  | 18.43  |
| P12H33         | 15.31                         | 15.72                               | 17.60  | 21.87  | 23.62  | 15.54                           | 18.25  | 20.80  | 23.76  | 13.94                           | 17.87  | 20.64  | 20.51  |
| P12H34         | 15.95                         | 14.70                               | 16.53  | 20.36  | 22.70  | 14.81                           | 17.21  | 19.54  | 23.04  | 13.74                           | 17.15  | 19.62  | 20.30  |
| P12H35         | 16.58                         | 13.90                               | 15.45  | 18.75  | 21.89  | 13.61                           | 15.97  | 17.32  | 21.59  | 12.51                           | 15.92  | 18.28  | 19.88  |

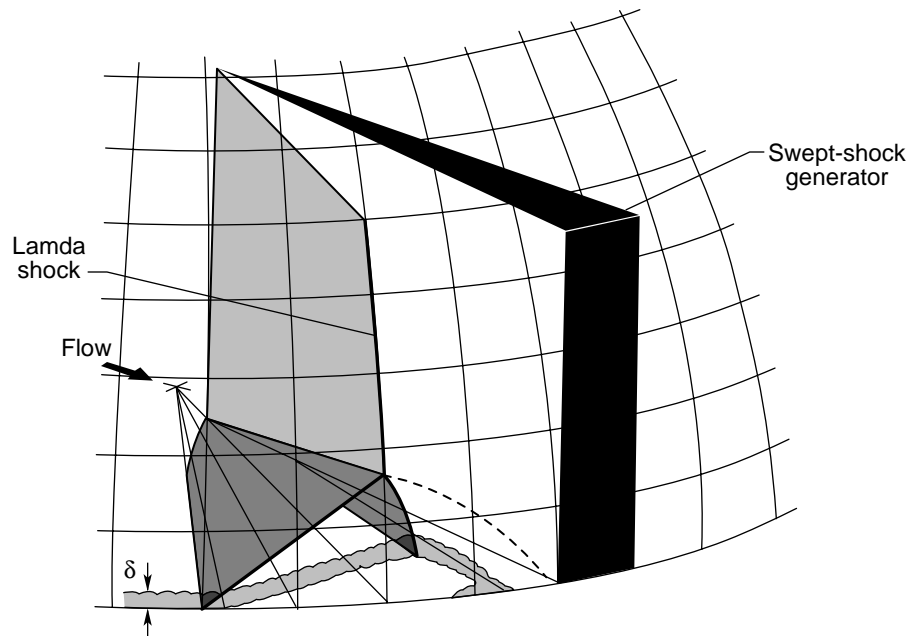


Table IX. Swept-Shock Pressure Distribution Data With Hydrogen Coolant

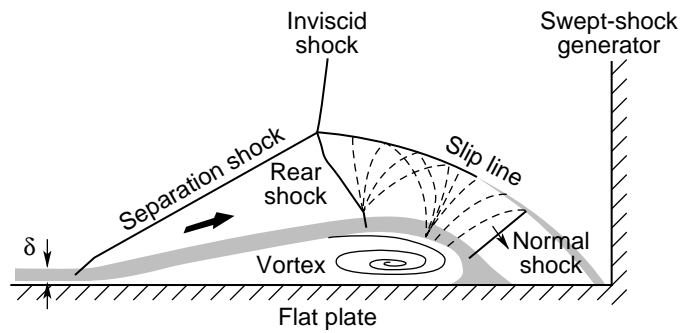
| Gauge<br>label | Distance<br>from<br>slot, in. | Pressure, psia |        |        |        |                                 |        |        |        |                                 |        |        |        |
|----------------|-------------------------------|----------------|--------|--------|--------|---------------------------------|--------|--------|--------|---------------------------------|--------|--------|--------|
|                |                               | No coolant     |        |        |        | $m = 0.260$ ( $p_c/p_e = 1.0$ ) |        |        |        | $m = 0.662$ ( $p_c/p_e = 2.0$ ) |        |        |        |
|                |                               | Pos. 1         | Pos. 2 | Pos. 3 | Pos. 4 | Pos. 1                          | Pos. 2 | Pos. 3 | Pos. 4 | Pos. 1                          | Pos. 2 | Pos. 3 | Pos. 4 |
| P5P10          | 0.64                          | 0.39           | 0.37   | 0.40   | 0.53   | 0.96                            | 0.91   | 0.93   | 0.96   | 1.14                            | 1.12   | 1.12   | 1.15   |
| P5P1           | 0.73                          | 0.97           | 0.92   | 1.21   | 1.23   | 1.30                            | 1.29   | 1.38   | 1.37   | 1.48                            | 1.49   | 1.50   | 1.47   |
| P5P12          | 1.15                          | 1.20           | 1.08   | 1.00   | 1.24   | 1.69                            | 1.57   | 1.50   | 1.50   | 1.81                            | 1.69   | 1.59   | 1.63   |
| P5P2           | 1.25                          | 1.34           | 1.29   | 1.40   | 1.48   | 1.74                            | 1.68   | 1.69   | 1.68   | 1.77                            | 1.67   | 1.66   | 1.69   |
| P5P14          | 1.62                          | 1.51           | 1.35   | 1.23   | 1.36   | 1.87                            | 1.74   | 1.66   | 1.59   | 1.99                            | 1.87   | 1.71   | 1.65   |
| P5P3           | 1.76                          | 1.54           | 1.44   | 1.45   | 1.52   | 1.83                            | 1.71   | 1.67   | 1.62   | 1.93                            | 1.79   | 1.67   | 1.68   |
| P5P16          | 2.18                          | 1.82           | 1.65   | 1.50   | 1.56   | 2.00                            | 1.87   | 1.78   | 1.70   | 2.16                            | 2.04   | 1.88   | 1.76   |
| P5P4           | 2.26                          | 1.65           | 1.54   | 1.53   | 1.55   | 1.88                            | 1.78   | 1.68   | 1.64   | 2.01                            | 1.90   | 1.75   | 1.71   |
| P5P5           | 2.77                          | 1.72           | 1.58   | 1.52   | 1.55   | 1.85                            | 1.74   | 1.64   | 1.60   | 2.00                            | 1.89   | 1.75   | 1.70   |
| P5P6           | 3.27                          | 1.77           | 1.59   | 1.50   | 1.51   | 1.82                            | 1.70   | 1.59   | 1.57   | 2.00                            | 1.88   | 1.75   | 1.69   |
| P5P8           | 4.27                          | 2.16           | 1.88   | 1.59   | 1.62   | 2.07                            | 1.94   | 1.83   | 1.77   | 2.33                            | 2.20   | 2.09   | 1.92   |
| P5P9           | 4.77                          | 1.72           | 1.53   | 1.29   | 1.24   | 1.69                            | 1.53   | 1.47   | 1.42   | 1.83                            | 1.75   | 1.66   | 1.57   |
| P12P1          | 5.72                          | 1.84           | 1.48   | 1.41   | 1.39   | 1.59                            | 1.62   | 1.58   | 1.57   | 1.87                            | 1.78   | 1.72   | 1.70   |
| P12P3          | 7.00                          | 1.62           | 1.38   | 1.28   | 1.37   | 1.43                            | 1.45   | 1.46   | 1.44   | 1.66                            | 1.62   | 1.62   | 1.60   |
| P12P5          | 8.28                          | 1.82           | 1.59   | 1.41   | 1.47   | 1.64                            | 1.51   | 1.51   | 1.49   | 1.68                            | 1.66   | 1.66   | 1.65   |
| P12P7          | 9.56                          | 1.83           | 1.64   | 1.50   | 1.47   | 1.78                            | 1.55   | 1.44   | 1.46   | 1.66                            | 1.56   | 1.57   | 1.58   |
| P12P8          | 10.20                         | 1.86           | 1.64   | 1.51   | 1.44   | 1.76                            | 1.57   | 1.42   | 1.37   | 1.64                            | 1.50   | 1.48   | 1.49   |
| P12P9          | 10.84                         | 1.77           | 1.62   | 1.46   | 1.37   | 1.70                            | 1.54   | 1.36   | 1.28   | 1.60                            | 1.45   | 1.40   | 1.43   |
| P12P10         | 11.48                         | 1.81           | 1.76   | 1.53   | 1.39   | 1.76                            | 1.61   | 1.43   | 1.29   | 1.64                            | 1.50   | 1.40   | 1.42   |
| P12P11         | 12.12                         | 1.83           | 1.82   | 1.64   | 1.42   | 1.81                            | 1.65   | 1.51   | 1.31   | 1.70                            | 1.59   | 1.44   | 1.43   |
| P12P12         | 12.76                         | 2.00           | 1.98   | 1.84   | 1.61   | 1.96                            | 1.87   | 1.74   | 1.51   | 1.85                            | 1.80   | 1.65   | 1.63   |
| P12P13         | 13.40                         | 2.02           | 2.00   | 1.95   | 1.67   | 2.03                            | 2.00   | 1.83   | 1.59   | 1.95                            | 1.88   | 1.72   | 1.64   |
| P12P14         | 14.04                         | 1.61           | 1.77   | 1.67   | 1.45   | 1.63                            | 1.64   | 1.54   | 1.35   | 1.56                            | 1.61   | 1.47   | 1.37   |
| P12P15         | 14.68                         | 1.49           | 1.67   | 1.64   | 1.42   | 1.50                            | 1.59   | 1.51   | 1.32   | 1.44                            | 1.55   | 1.45   | 1.31   |
| P12P16         | 15.32                         | 1.52           | 1.68   | 1.75   | 1.52   | 1.52                            | 1.63   | 1.58   | 1.44   | 1.47                            | 1.59   | 1.53   | 1.39   |
| P12P17         | 15.96                         | 1.42           | 1.65   | 1.73   | 1.58   | 1.44                            | 1.61   | 1.61   | 1.50   | 1.40                            | 1.56   | 1.58   | 1.41   |



(a) Incident-shock two-dimensional flow field.

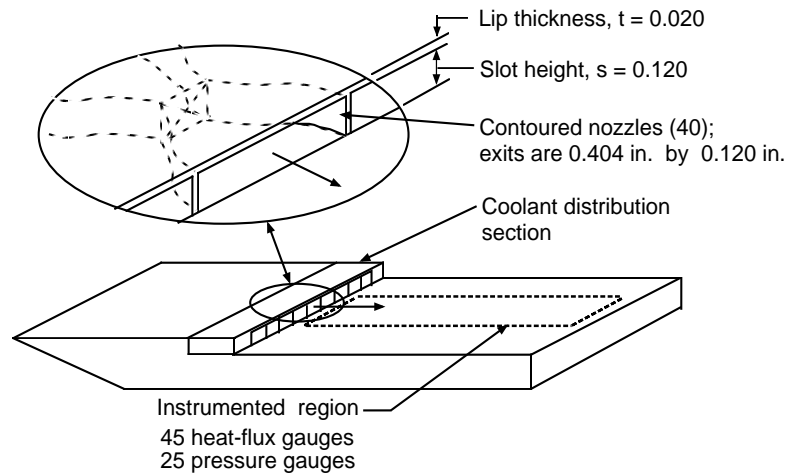


(b) Swept-shock quasi-conical interaction flow field. (From ref. 5.)

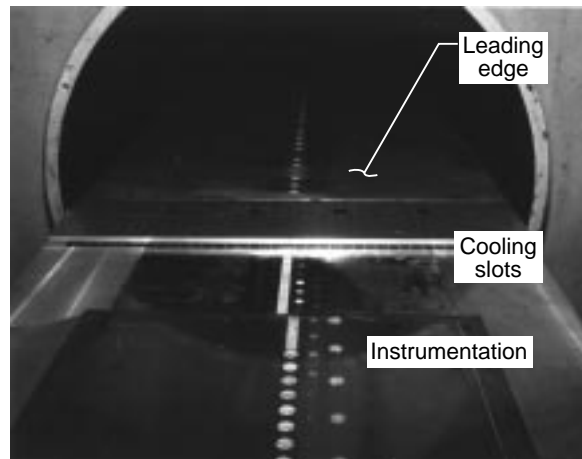


(c) Interaction flow field structure. Mach 3;  $\alpha = 20^\circ$ .

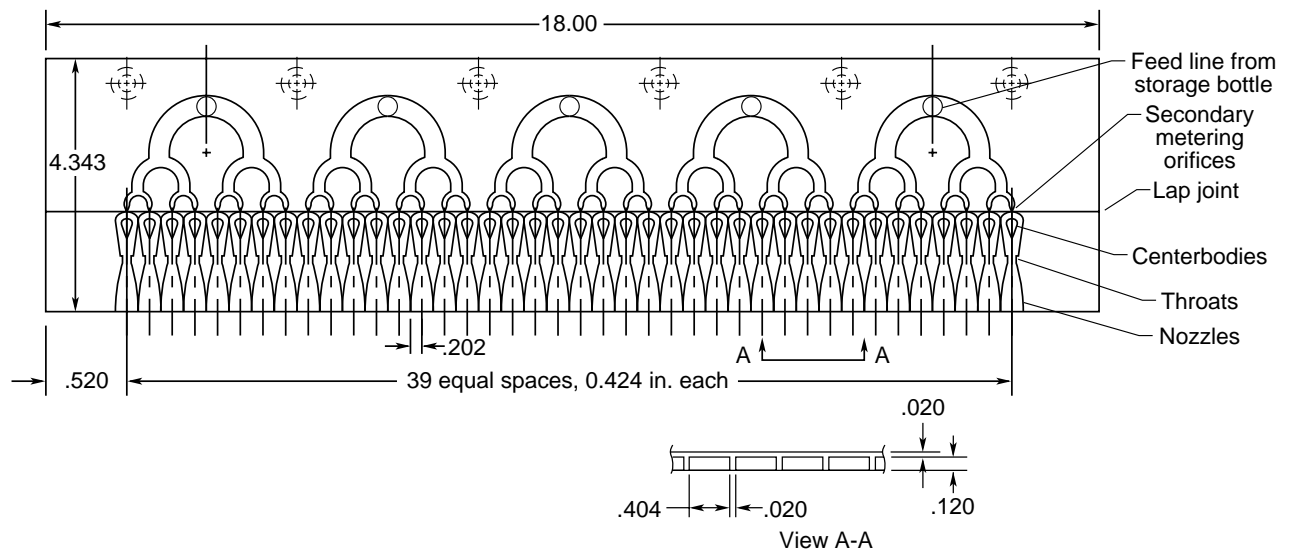
Figure 1. Oblique shock and turbulent boundary-layer interactions.



(a) Schematic of model.



(b) Photograph of model in tunnel.



(c) Coolant distribution section.

Figure 2. Slot cooling nozzles and coolant distribution system. All dimensions are in inches.

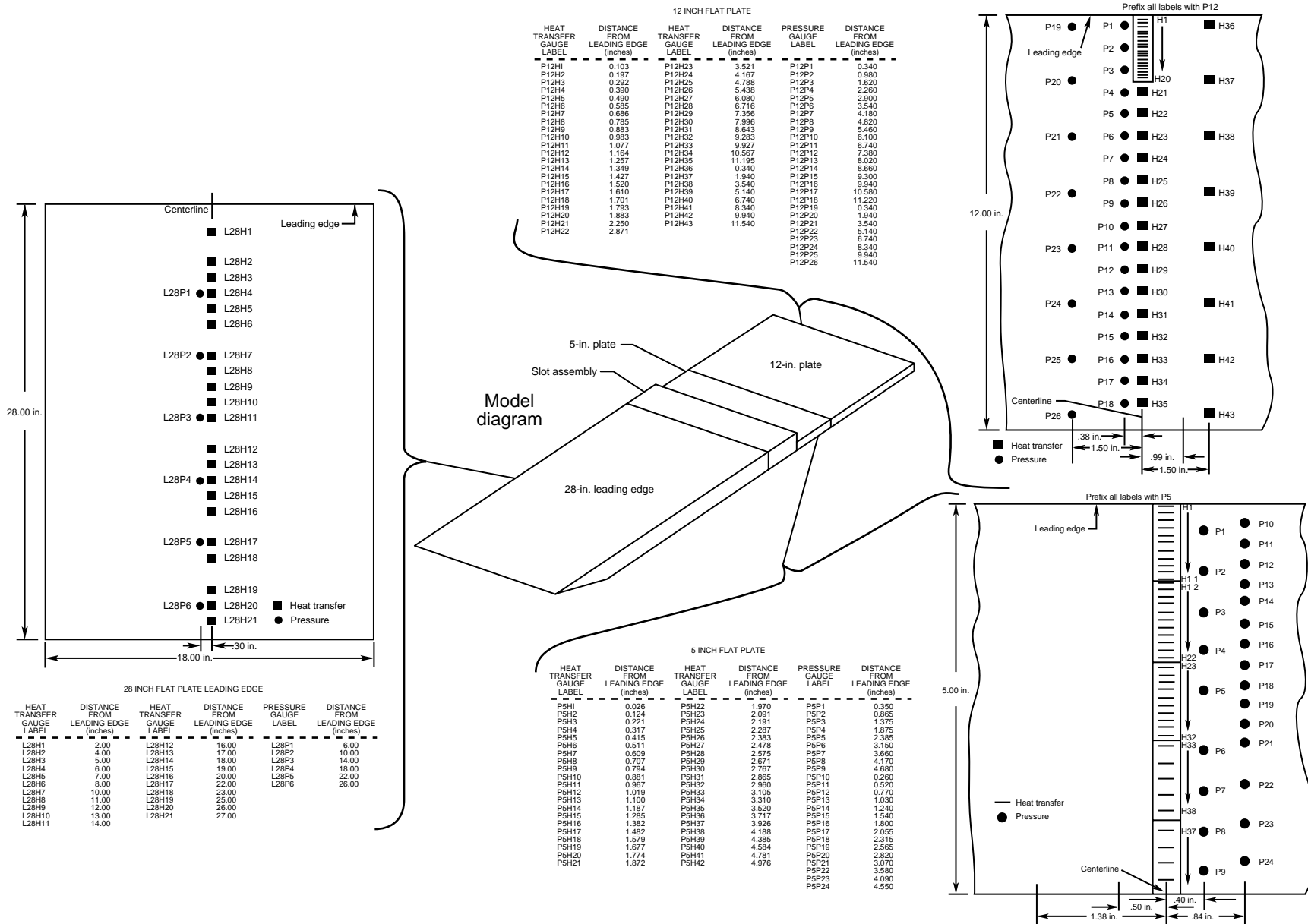
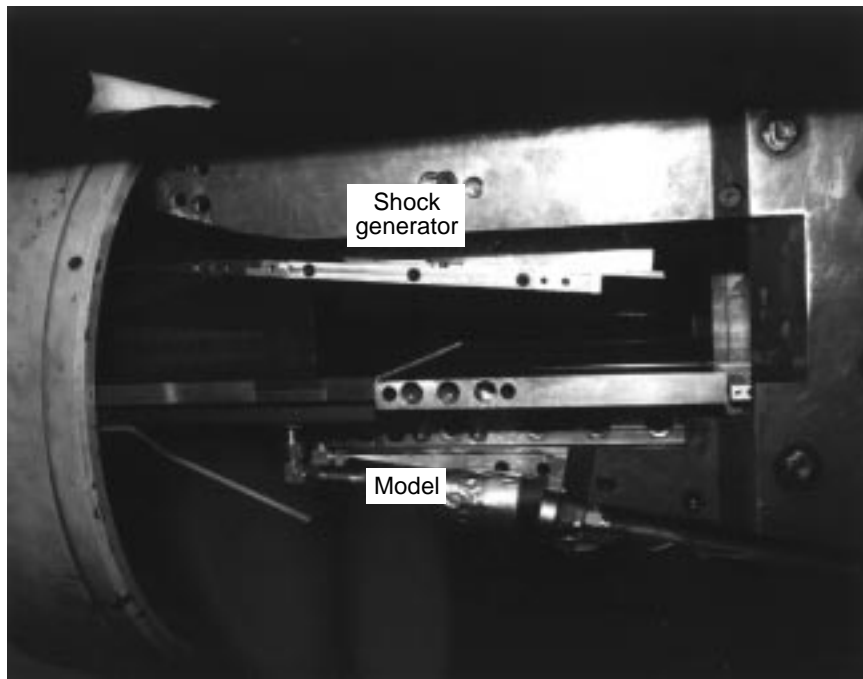
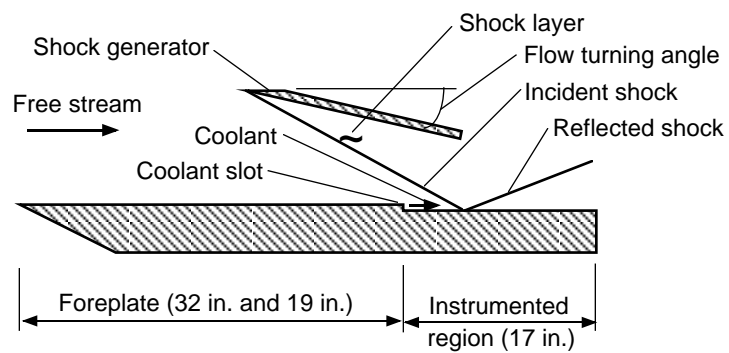


Figure 3. Model instrumentation layout.

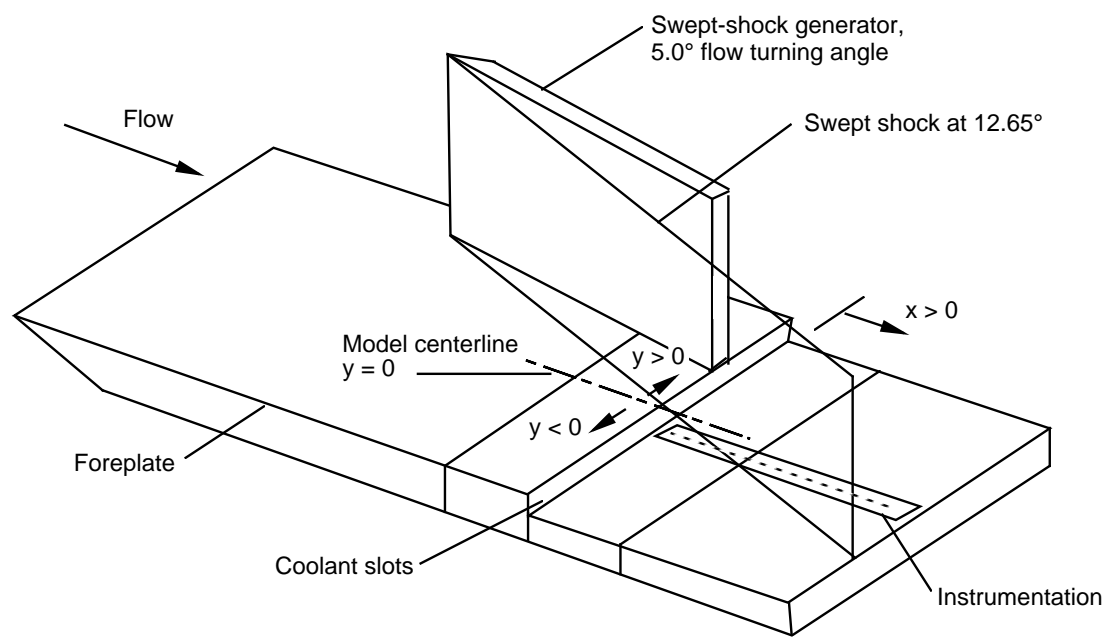


(a) Photograph.



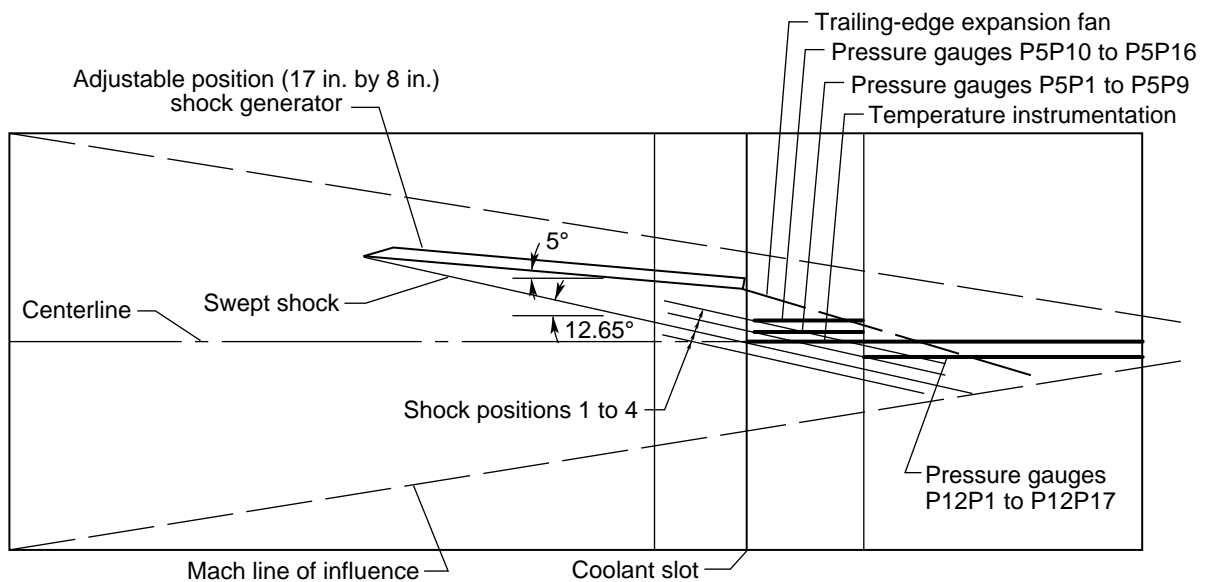
(b) Schematic.

Figure 4. Film cooling model and incident shock generator installed in Calspan 48-Inch Hypersonic Shock Tunnel.



(a) Front view.

Figure 5. Film-cooling model in swept-shock configuration.

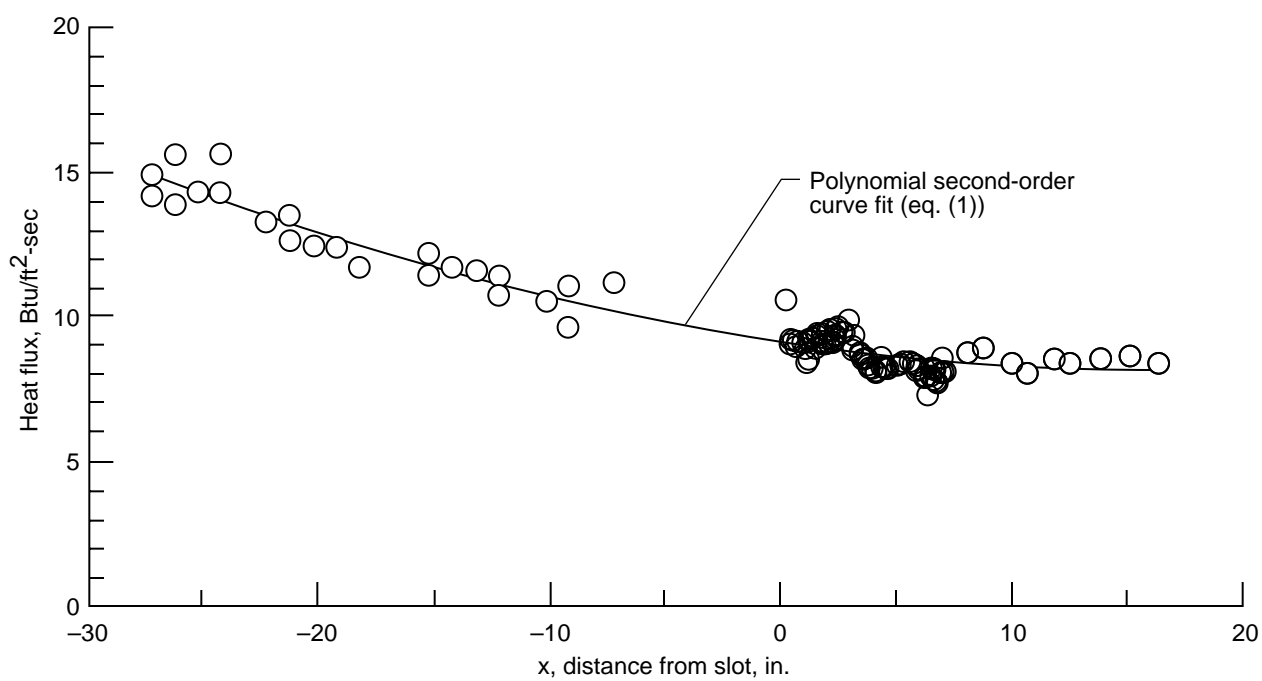


| Shock-instrumentation intersections |                          |  |                               |                               |                                 |
|-------------------------------------|--------------------------|--|-------------------------------|-------------------------------|---------------------------------|
| sShock position (fig. 5(b))         | Shock-slot crossing, in. | Temperature instrumentation (y = 0.0), in. | Pressure instrumentation, in. |                               |                                 |
|                                     |                          |  | *P5P1 to P5P9 (y = 0.40 in.)  | P5P10 to P5P24 (y = 0.84 in.) | P12P1 to P12P17 (y = -0.38 in.) |
| 1                                   | y = -0.424               | x = <0                                     | x = <0                        | x = <0                        | x = <0                          |
| 2                                   | y = 0.0                  | x = 0.0                                    | x = <0                        | x = <0                        | x = 1.7                         |
| 3                                   | y = +0.424               | x = 1.9                                    | x = 0.11                      | x = <0                        | x = 3.6                         |
| 4                                   | y = +0.848               | x = 3.8                                    | x = 2.01                      | x = 0.0                       | x = 5.5                         |

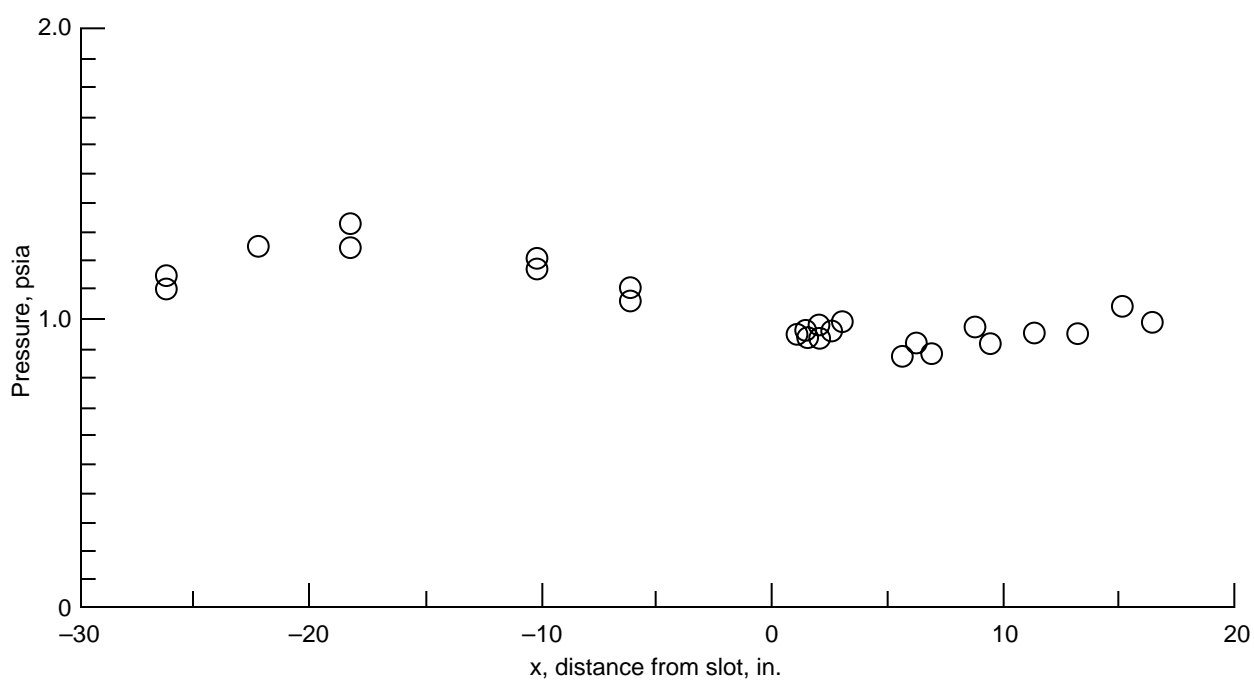
\*P5P1 means 5-in. flat plate and pressure gauge 1.

(b) Plan view.

Figure 5. Concluded.



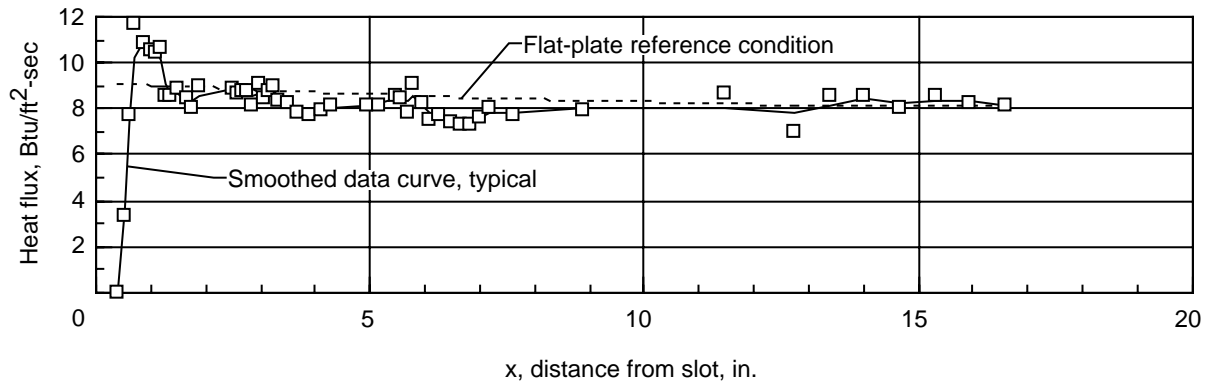
(a) Heat flux.



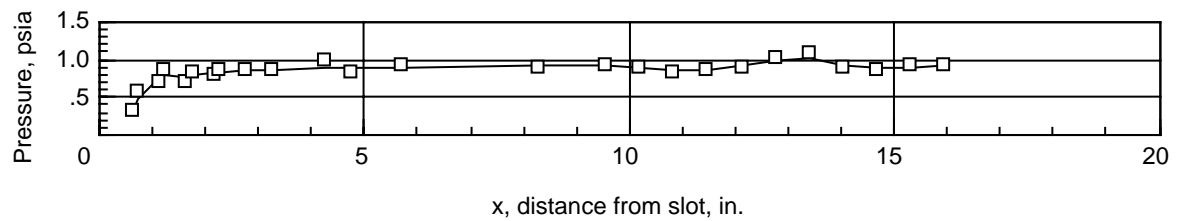
(b) Pressure.

Figure 6. Flat-plate reference conditions at  $M_\infty = 6.4$ ,  $T_0 = 2126^\circ\text{R}$ ,  $p_0 = 2354$  psia, and  $R_\infty = 8 \times 10^6/\text{ft}$ .



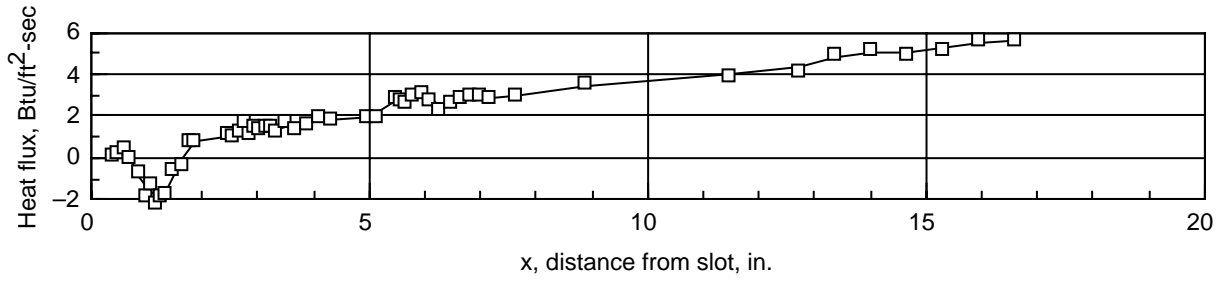


(a) Heat flux.

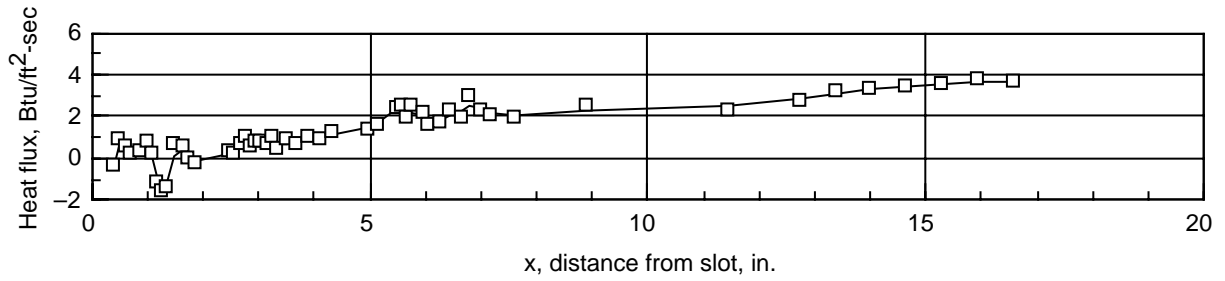


(b) Pressure.

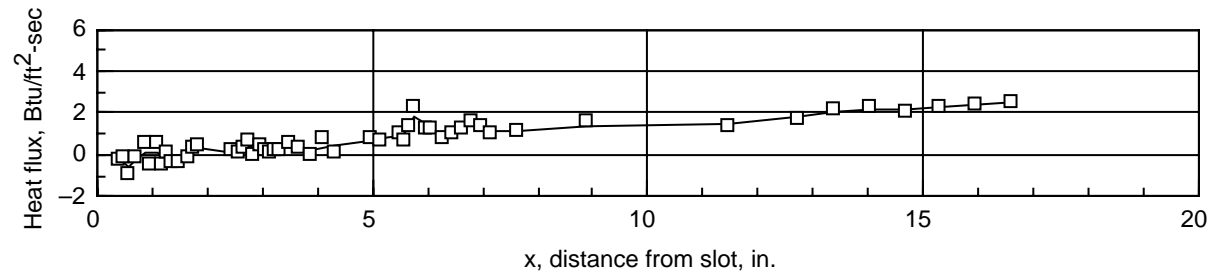
Figure 7. Baseline configuration with no coolant.



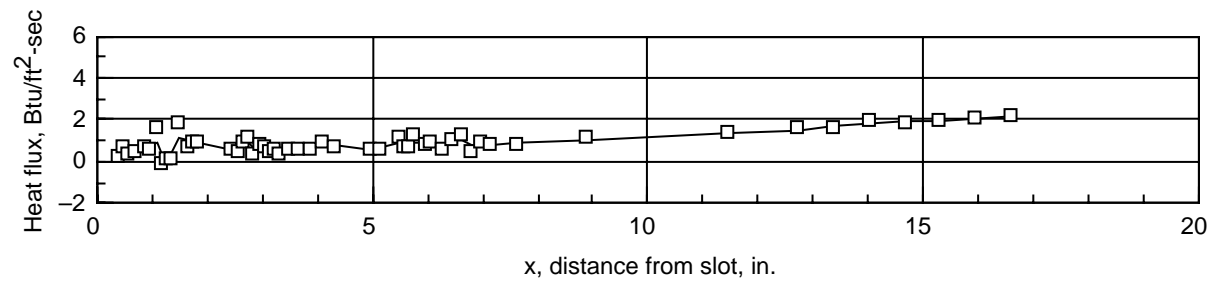
(a)  $m_c = 0.163 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 0.5$ ).



(b)  $m_c = 0.260 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.0$ ).

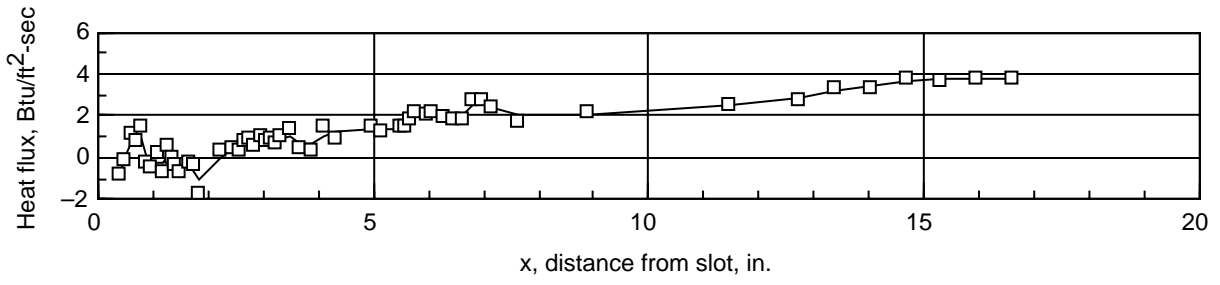


(c)  $m_c = 0.460 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.5$ ).

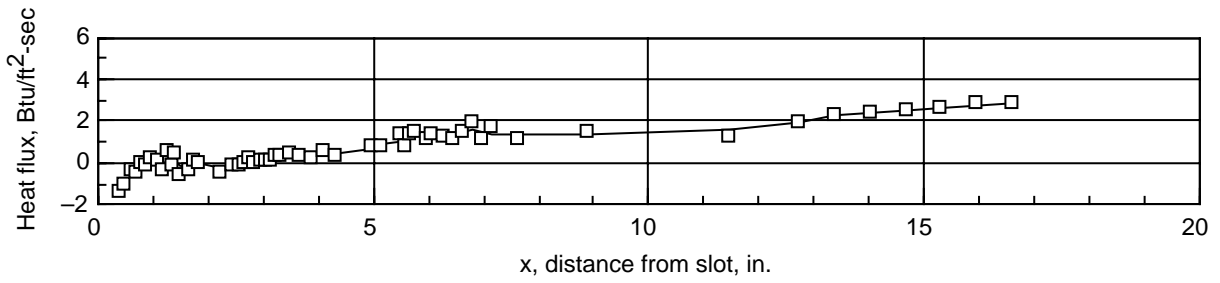


(d)  $m_c = 0.662 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 2.0$ ).

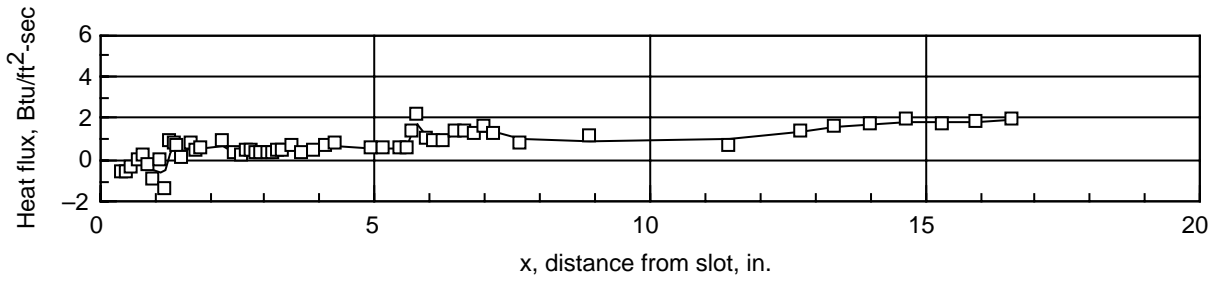
Figure 8. Heat-flux distributions of hydrogen film-cooling mass flow effects.



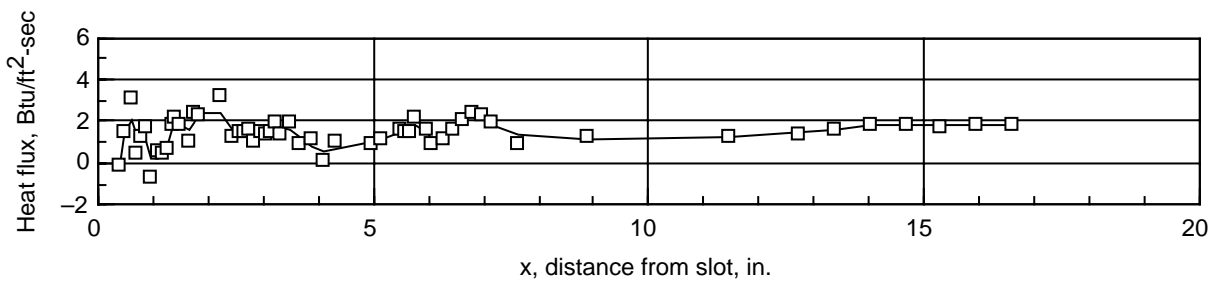
(a)  $m_c = 0.520 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 0.5$ ).



(b)  $m_c = 0.749 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.0$ ).

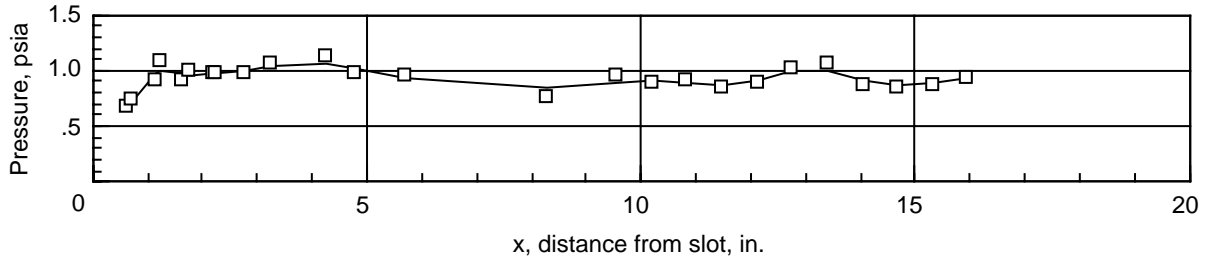


(c)  $m_c = 1.170 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.5$ ).

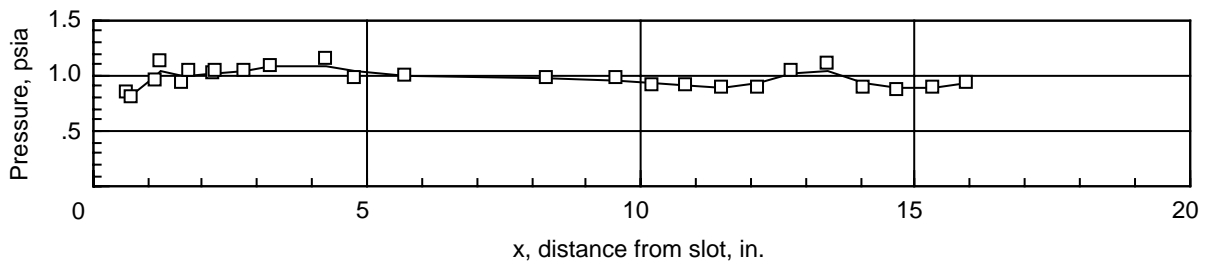


(d)  $m_c = 1.580 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 2.0$ ).

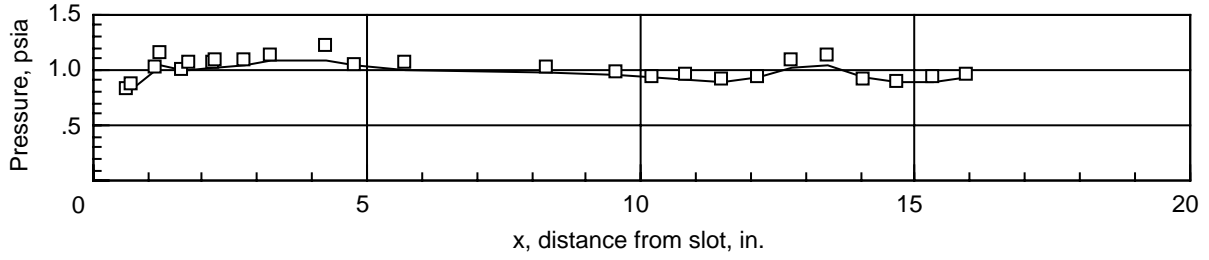
Figure 9. Heat-flux distributions of helium film-cooling mass flow effects.



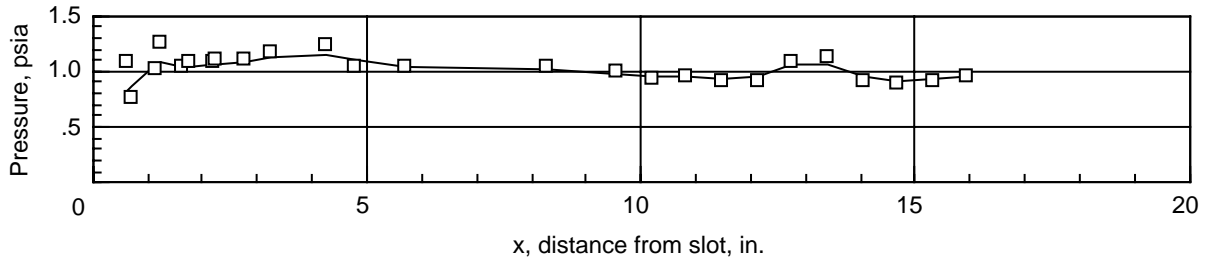
(a)  $m_c = 1.163 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 0.5$ ).



(b)  $m_c = 0.260 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.0$ ).

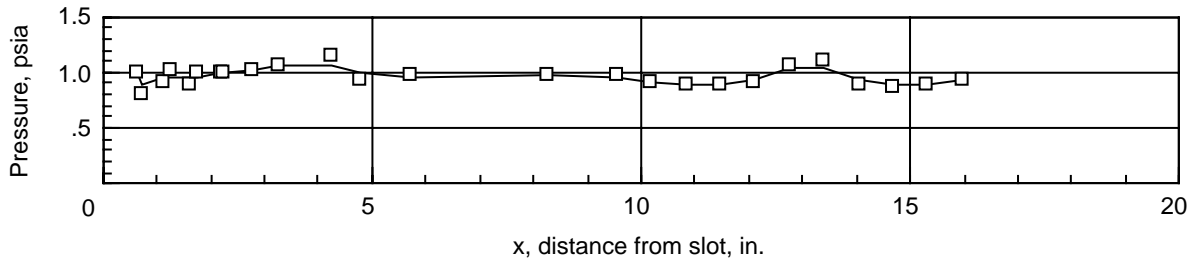


(c)  $m_c = 0.460 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.5$ ).

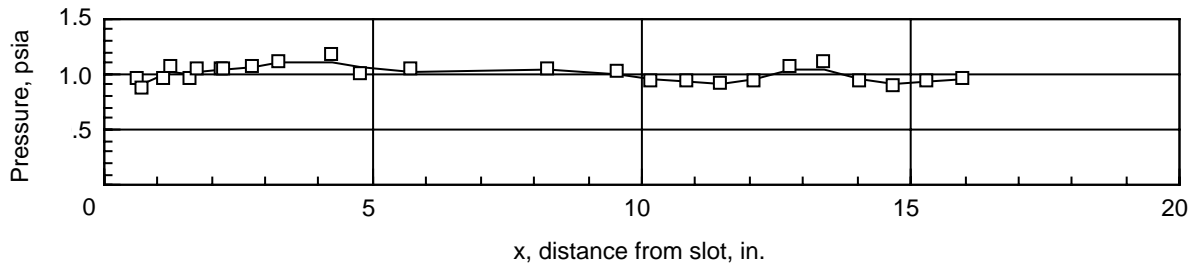


(d)  $m_c = 0.662 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 2.0$ ).

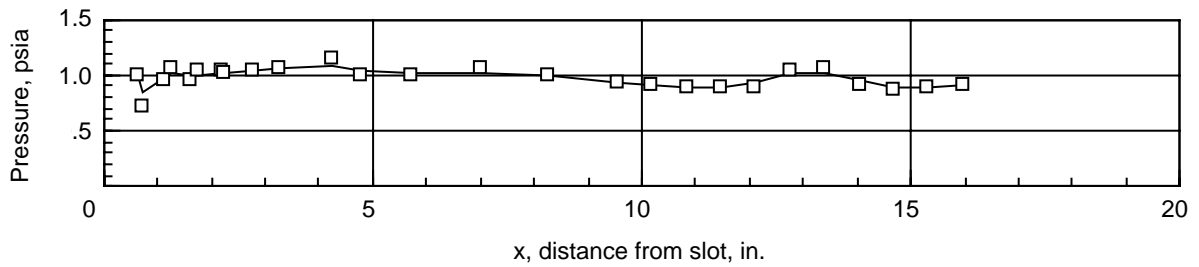
Figure 10. Pressure distributions of hydrogen film-cooling mass flow effects.



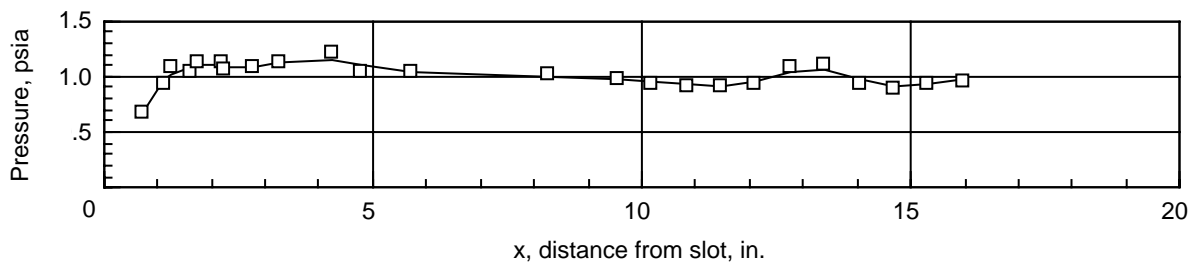
(a)  $m_c = 0.520 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 0.5$ ).



(b)  $m_c = 0.749 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.0$ ).

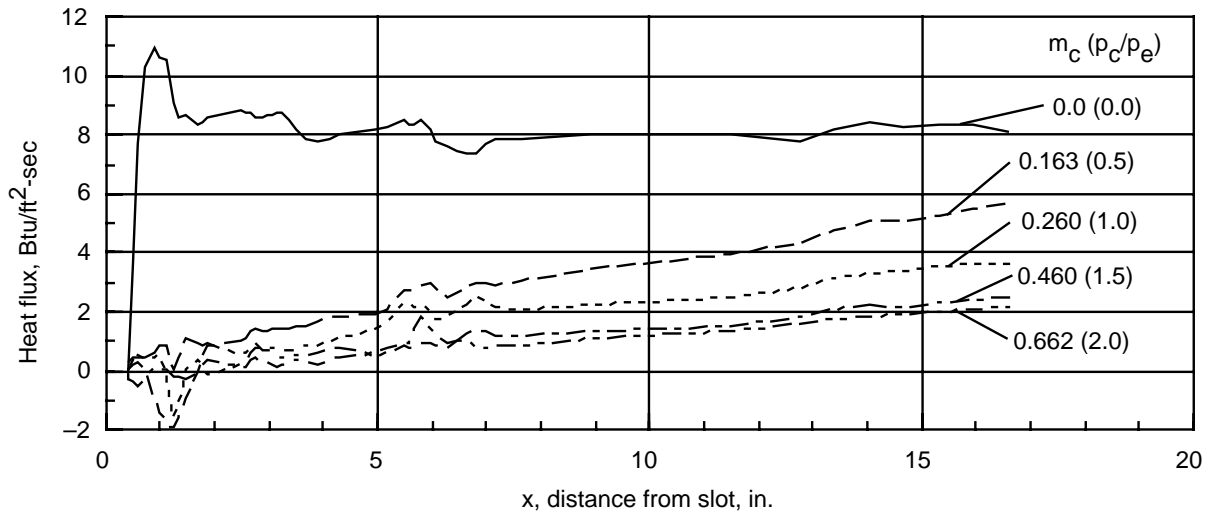


(c)  $m_c = 1.170 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 1.5$ ).

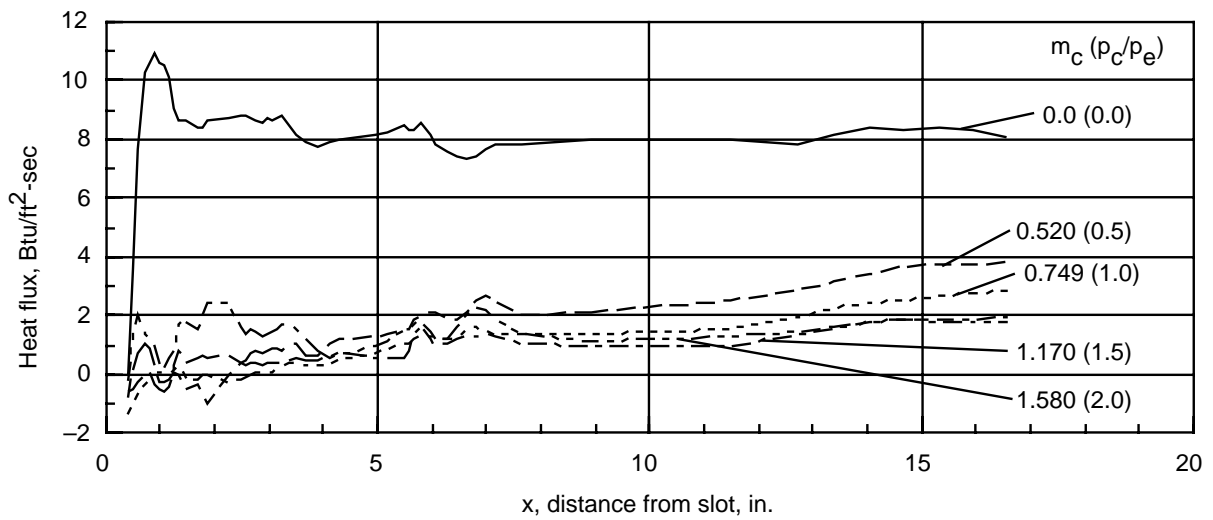


(d)  $m_c = 1.580 \text{ lbm/sec-in}^2$  ( $p_c/p_e = 2.0$ ).

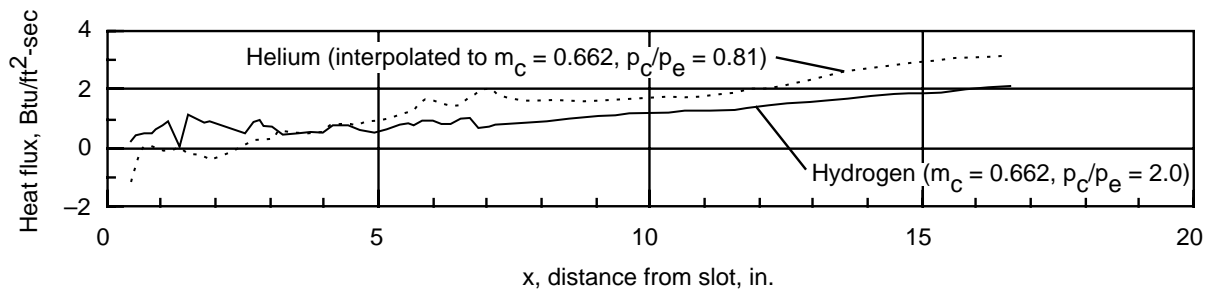
Figure 11. Pressure distributions of helium film-cooling mass flow effects.



(a) Hydrogen coolant.

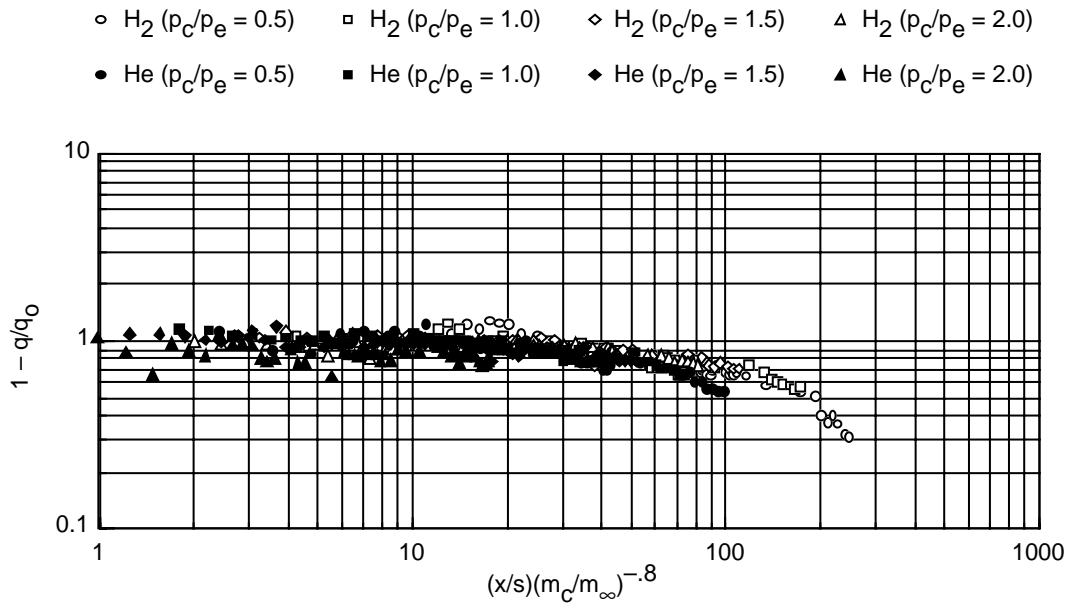


(b) Helium coolant.

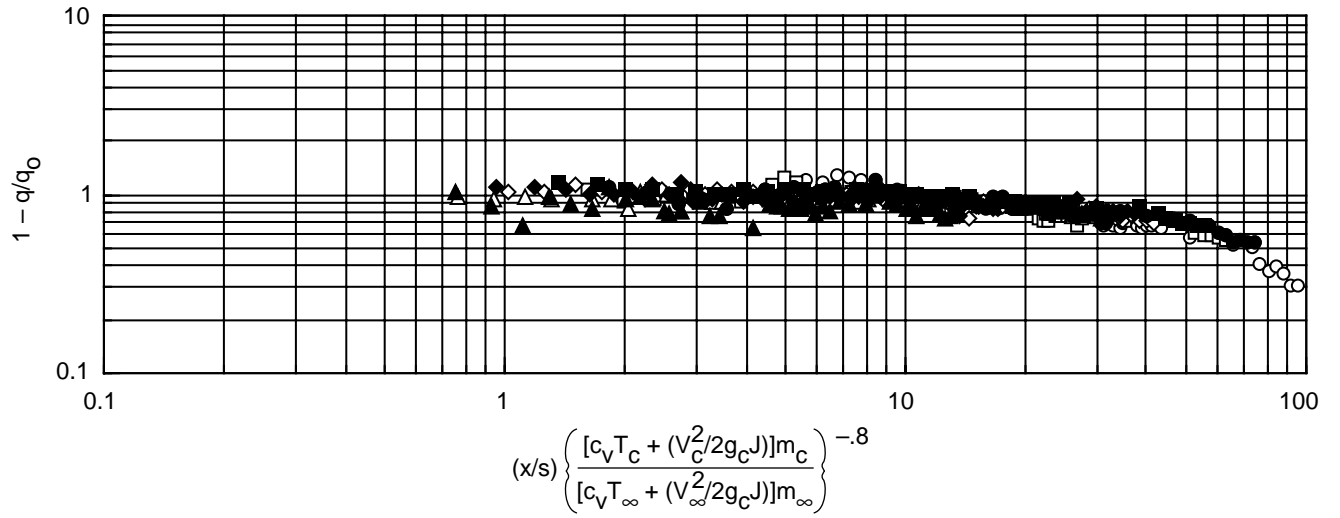


(c) Hydrogen and helium coolants at same mass flow rate.

Figure 12. Coolant mass flow effects on heat flux.

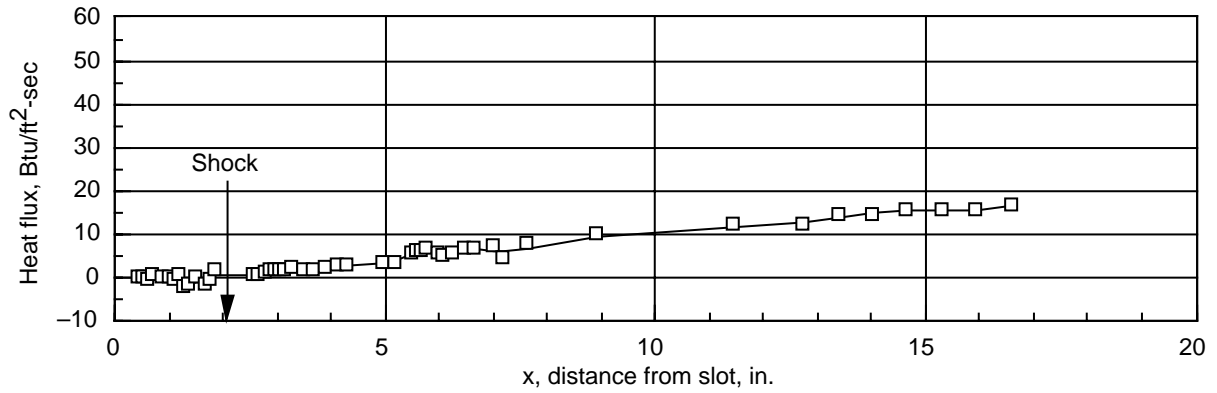


(a) Basic correlation.

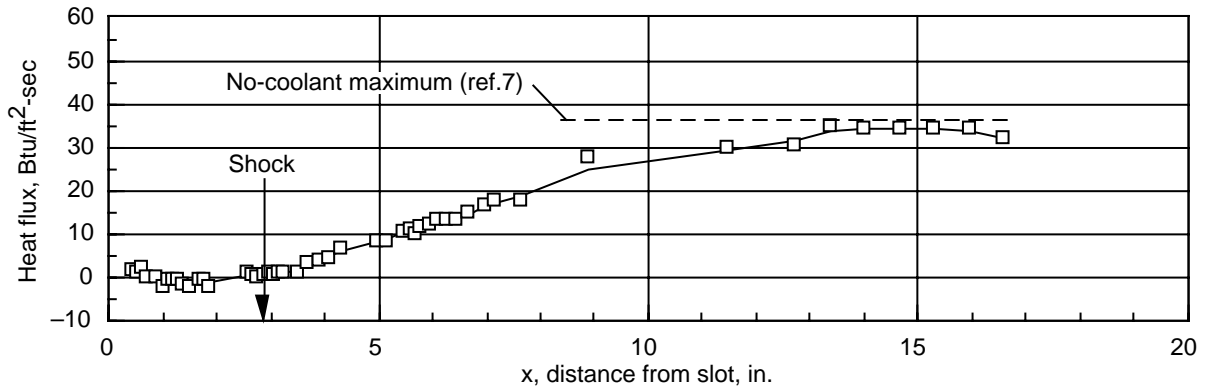


(b) Improved correlation.

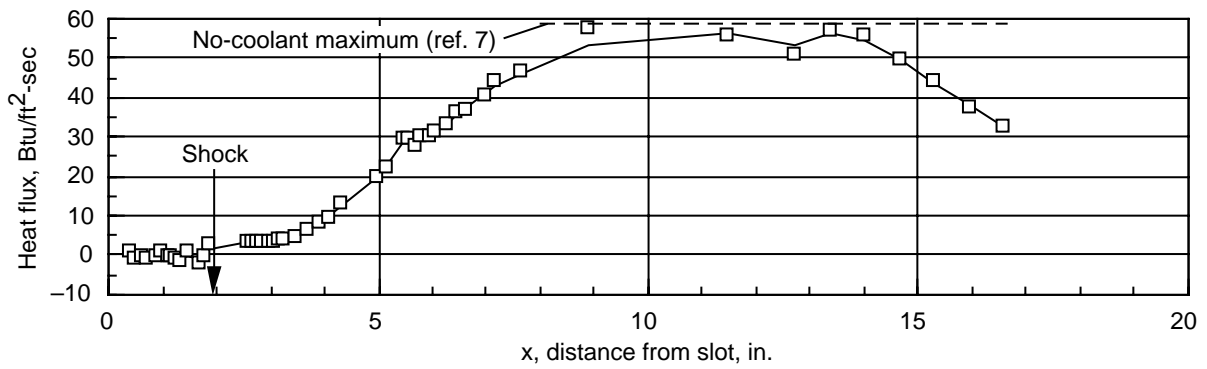
Figure 13. Film-cooling correlations.



(a) 2.5° incident shock.



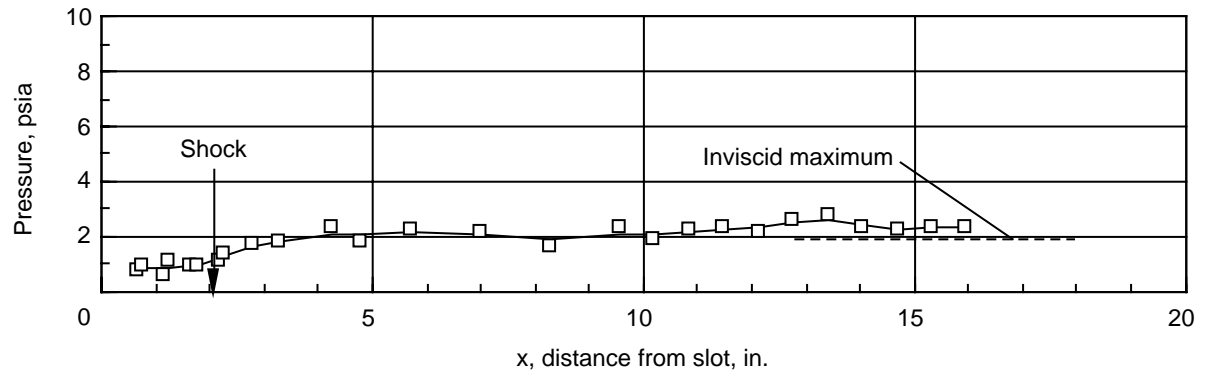
(b) 5.0° incident shock.



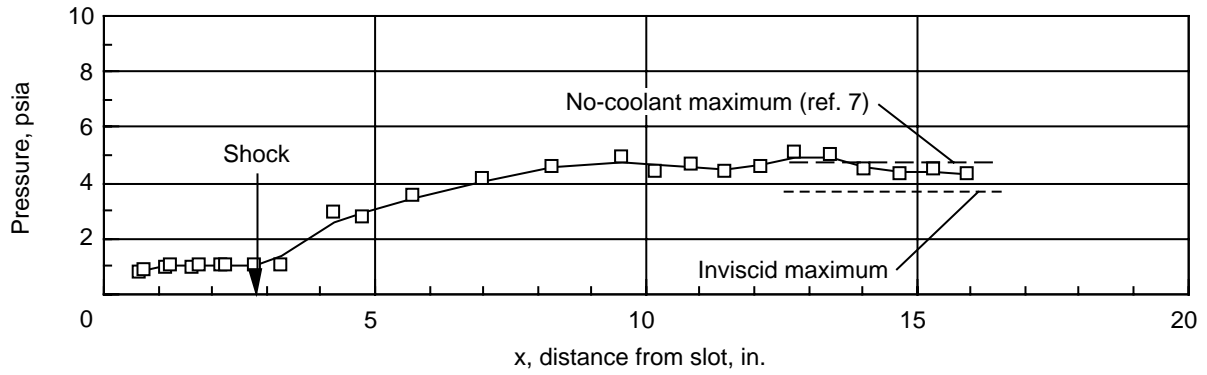
(c) 7.5° incident shock.

Figure 14. Incident-shock heat-flux distributions with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 19.8 \times 10^6$ .

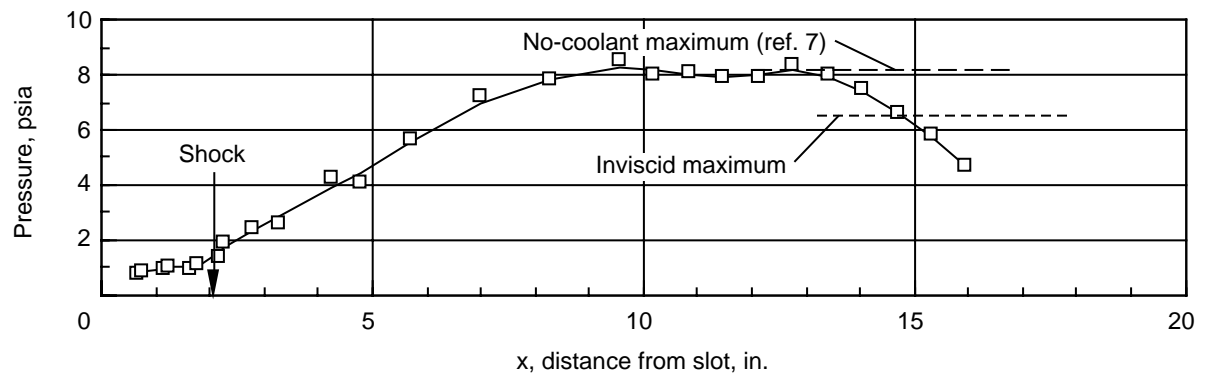




(a) 2.5° turning angle shock.

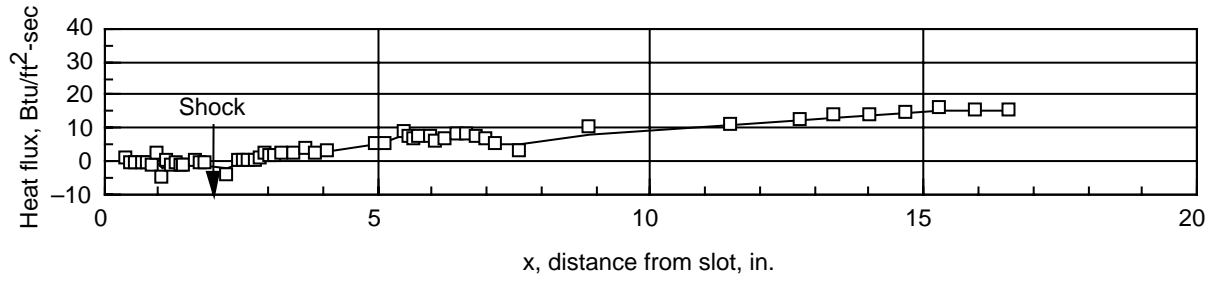


(b) 5.0° turning angle shock.

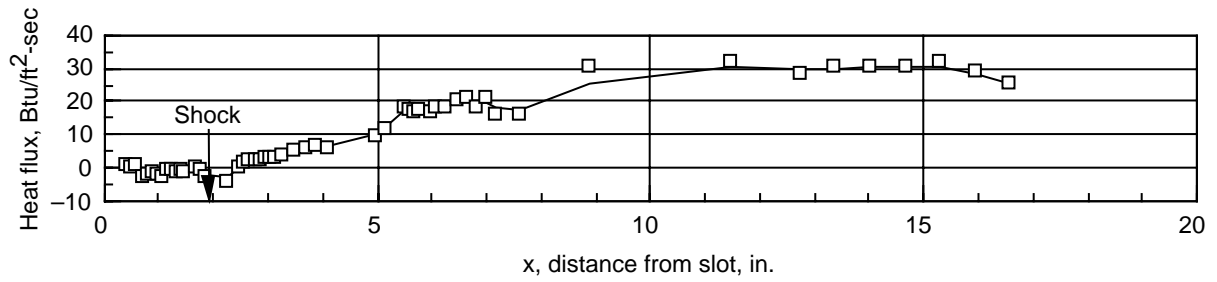


(c) 7.5° turning angle shock.

Figure 15. Incident-shock strength pressure distributions with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 19.8 \times 10^6$ .

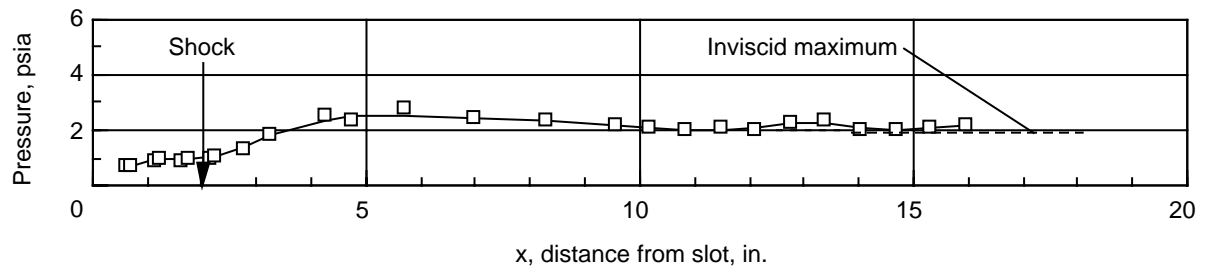


(a) 2.5° turning angle shock.

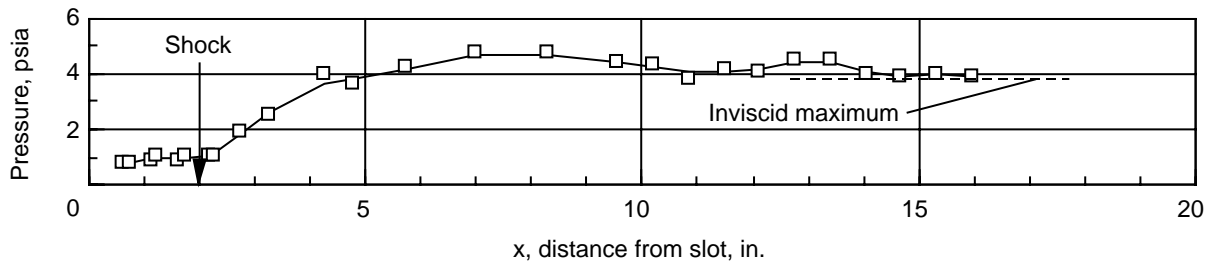


(b) 5.0° turning angle shock.

Figure 16. Incident-shock heat-flux distributions with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 11.75 \times 10^6$ .

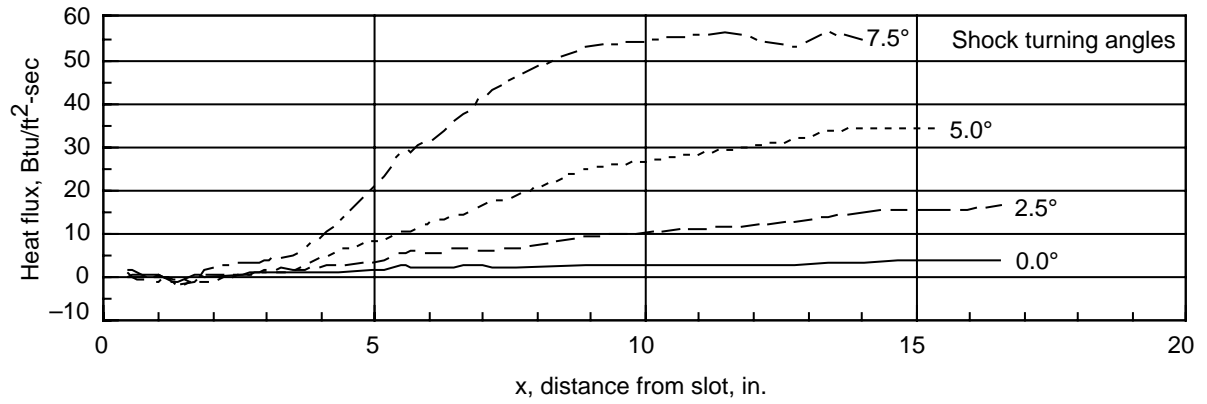


(a) 2.5° turning angle shock.

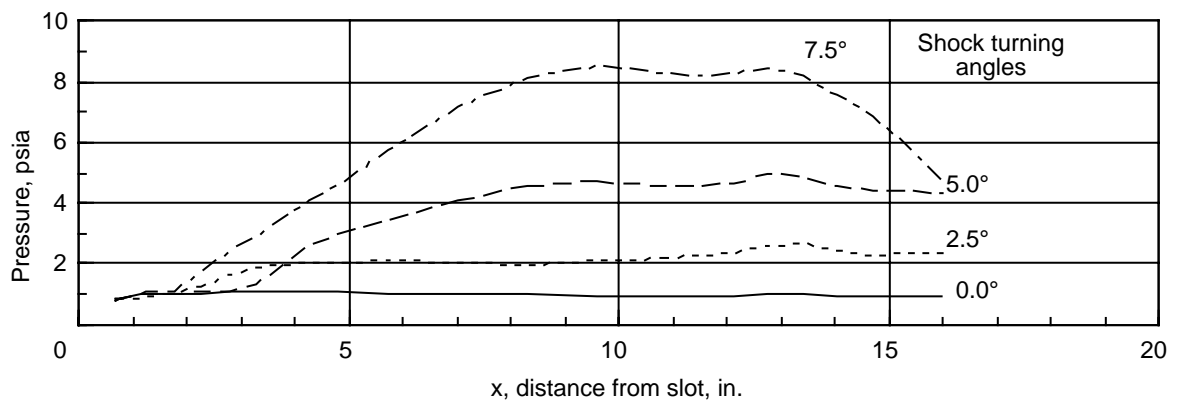


(b) 5.0° turning angle shock.

Figure 17. Incident-shock strength pressure distributions with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 11.75 \times 10^6$ .

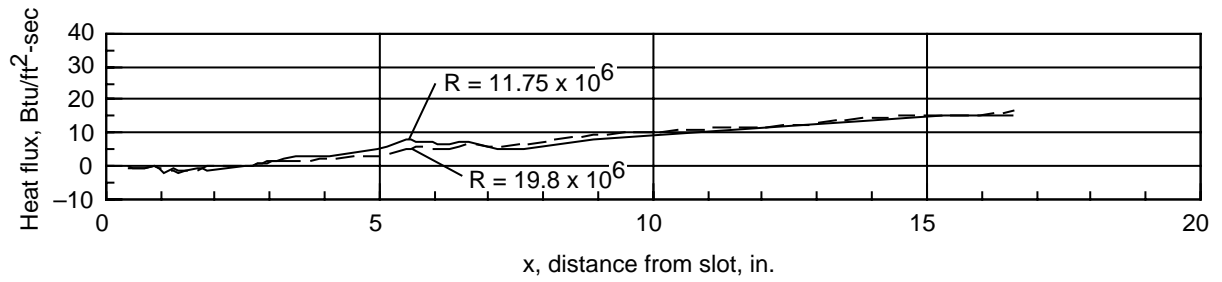


(a) Heat flux.

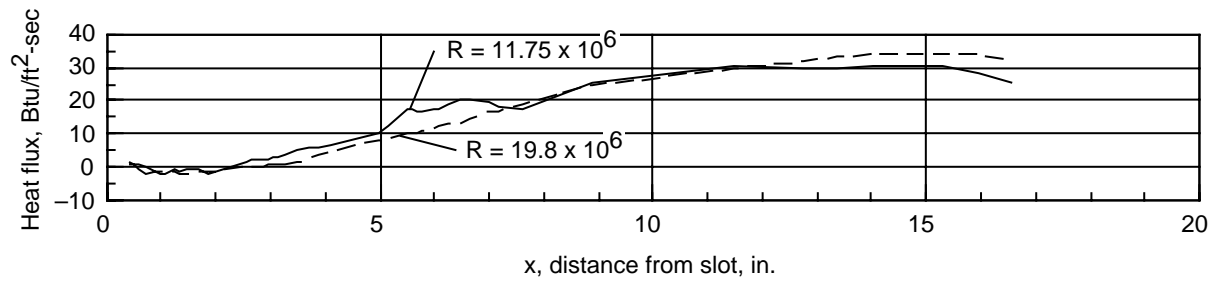


(b) Pressure.

Figure 18. Comparison of distributions for incident shock with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 19.8 \times 10^6$ .

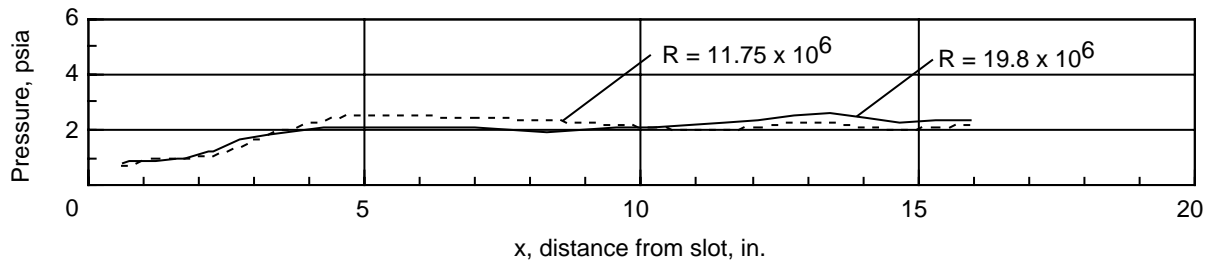


(a) 2.5° turning angle shock.

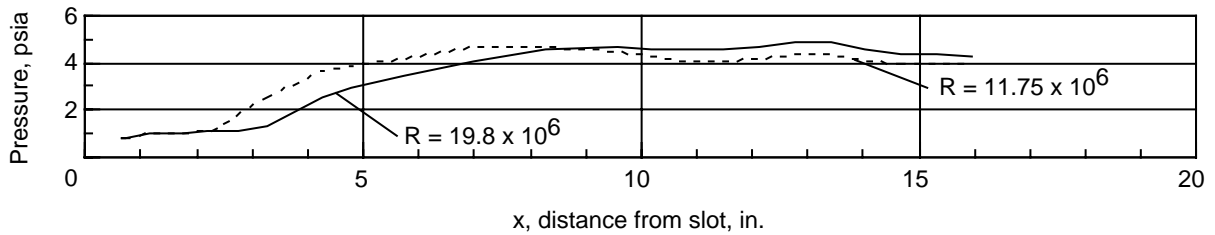


(b) 5.0° turning angle shock.

Figure 19. Comparison of heat-flux distributions with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 11.75 \times 10^6$  and  $19.8 \times 10^6$ .

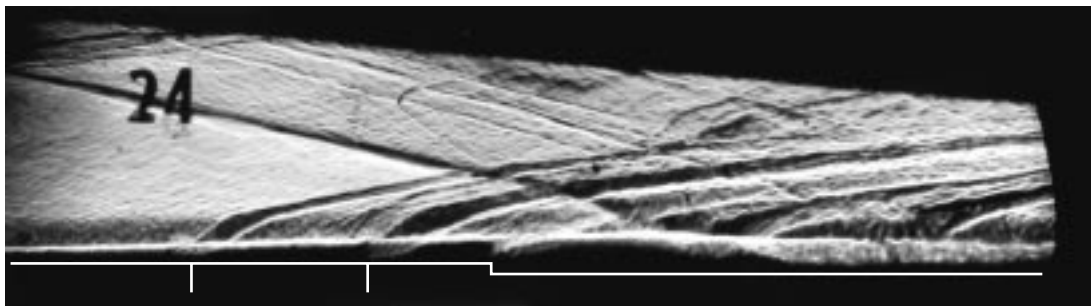


(a)  $2.5^\circ$  turning angle shock.

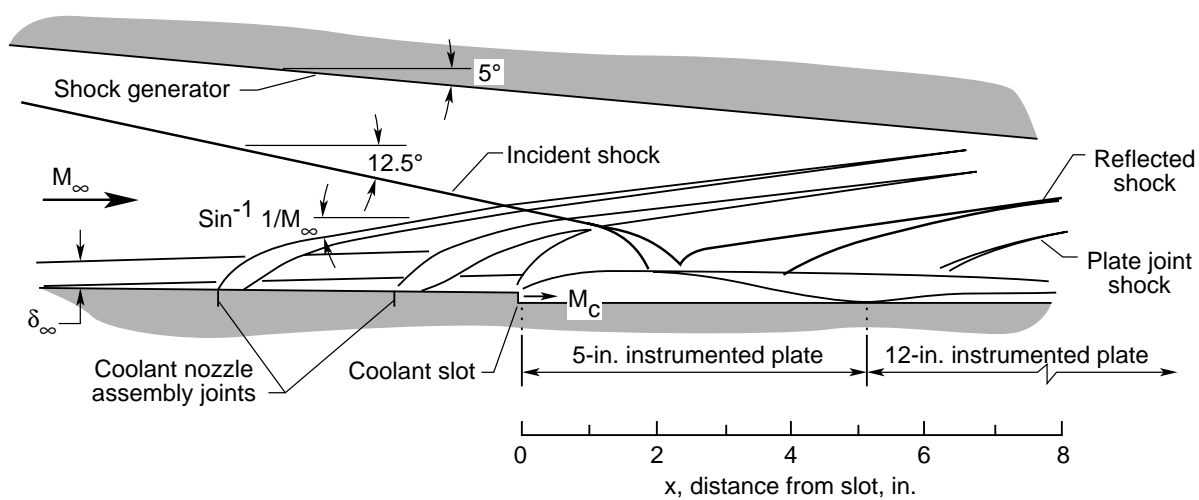


(b)  $5.0^\circ$  turning angle shock.

Figure 20. Comparison of pressure distribution data with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ) and  $R = 11.75 \times 10^6$  and  $19.8 \times 10^6$ .

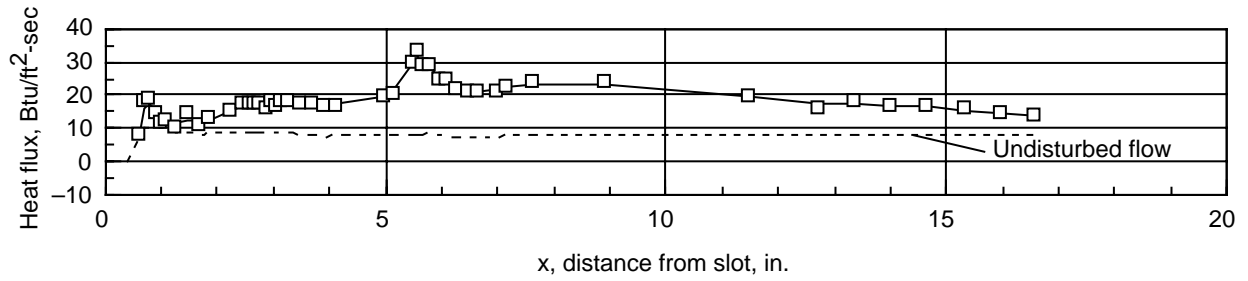


(a) Schlieren photograph.

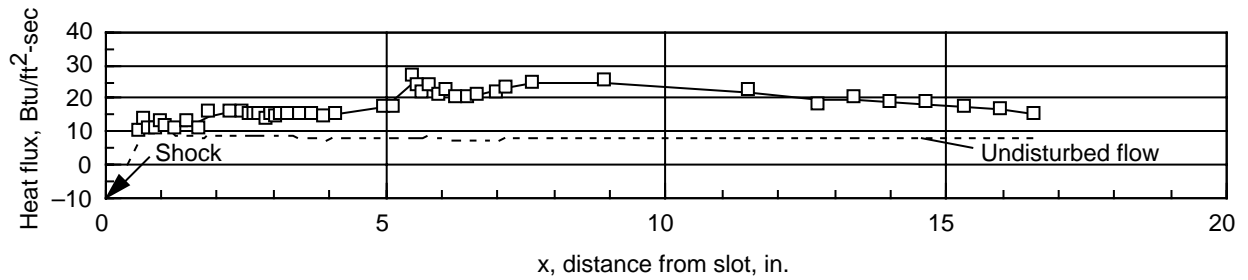


(b) Schematic.

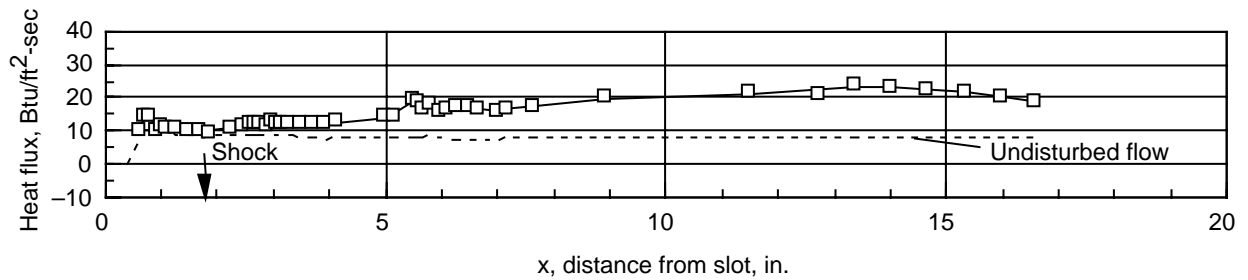
Figure 21. Flow-field visualization for 5.0° incident shock with  $R_\infty = 11.75 \times 10^6$  and hydrogen coolant at  $p_c/p_e = 1.0$ .



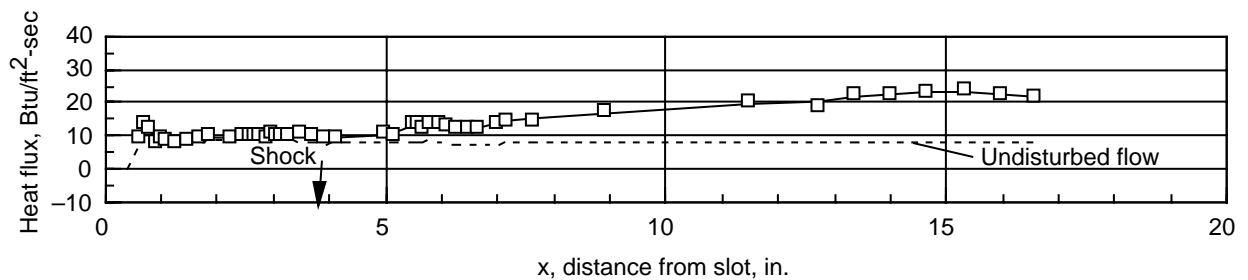
(a) Position 1 ( $y = -0.424$  in.).



(b) Position 2 ( $y = 0.0$  in.).



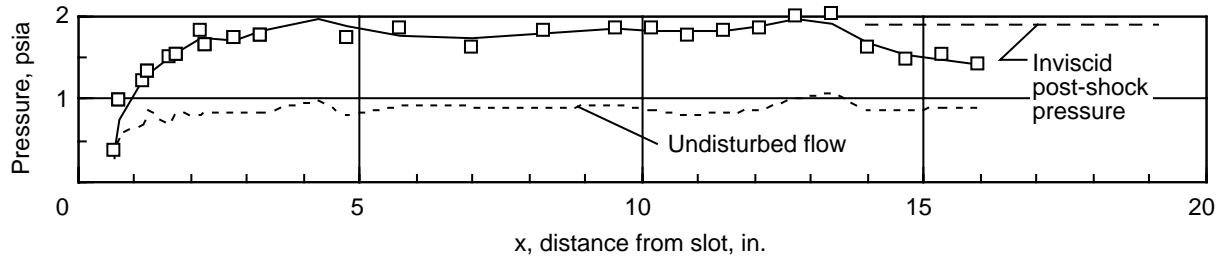
(c) Position 3 ( $y = 0.424$  in.).



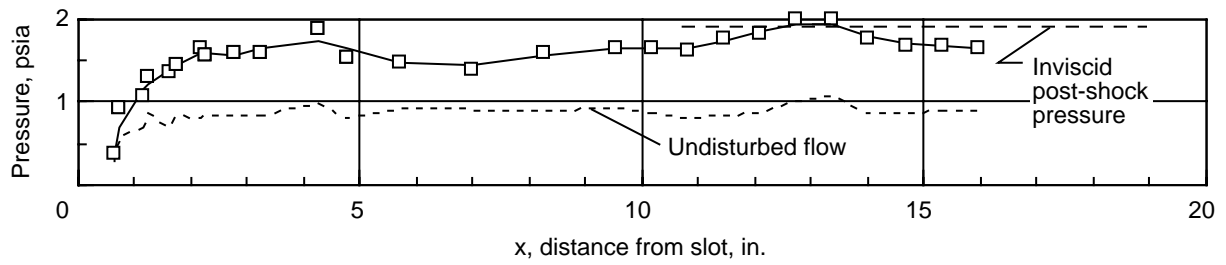
(d) Position 4 ( $y = 0.848$  in.).

Figure 22. Heat-flux distribution for 5° swept shock with no coolant.

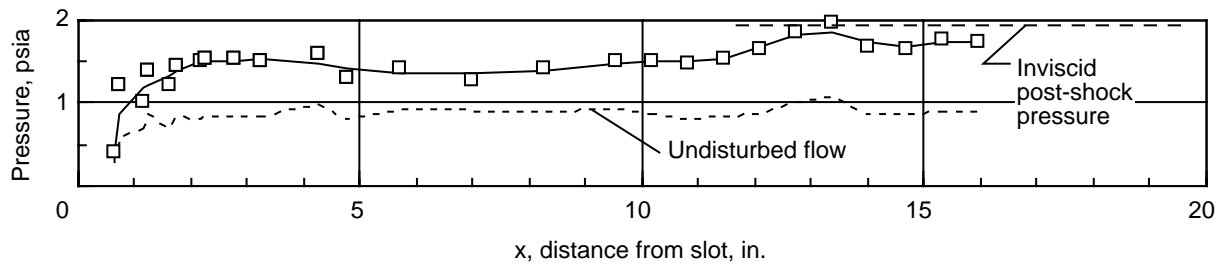




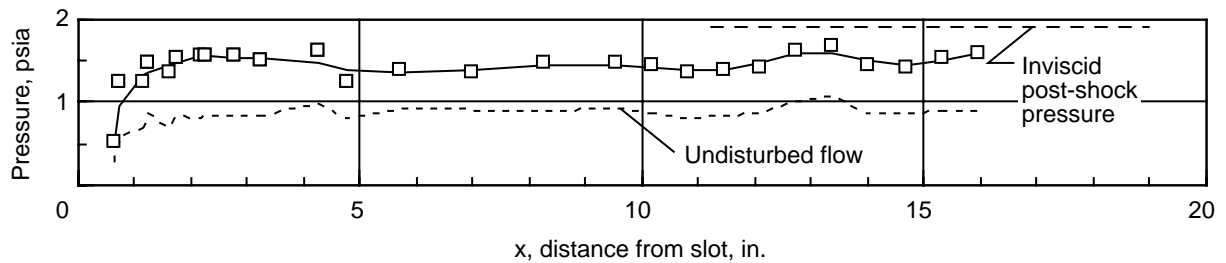
(a) Position 1 ( $y = -0.424$  in.).



(b) Position 2 ( $y = 0.0$  in.).

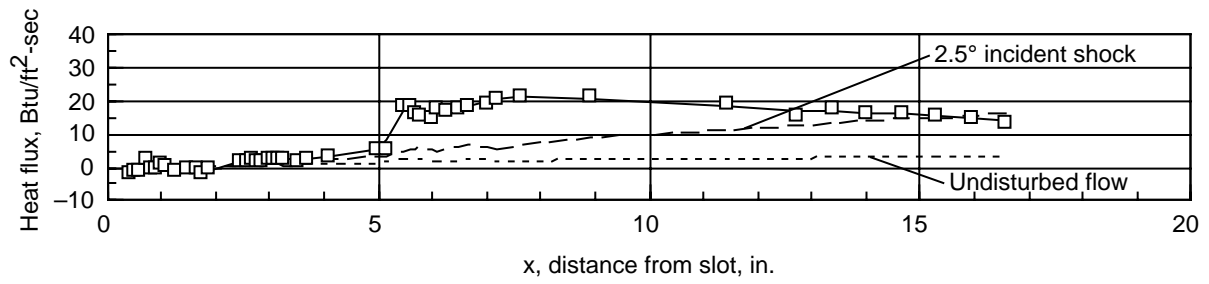


(c) Position 3 ( $y = 0.424$  in.).

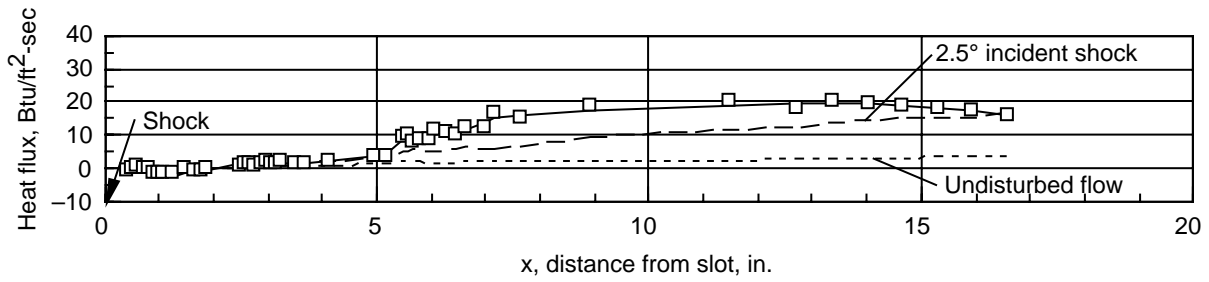


(d) Position 4 ( $y = 0.848$  in.).

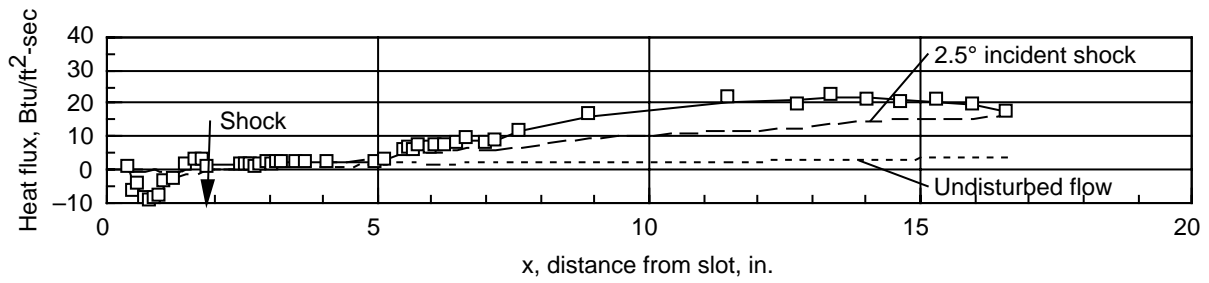
Figure 23. Pressure distribution for  $5^\circ$  swept shock with no coolant. (See fig. 5 for shock-instrumentation intersections.)



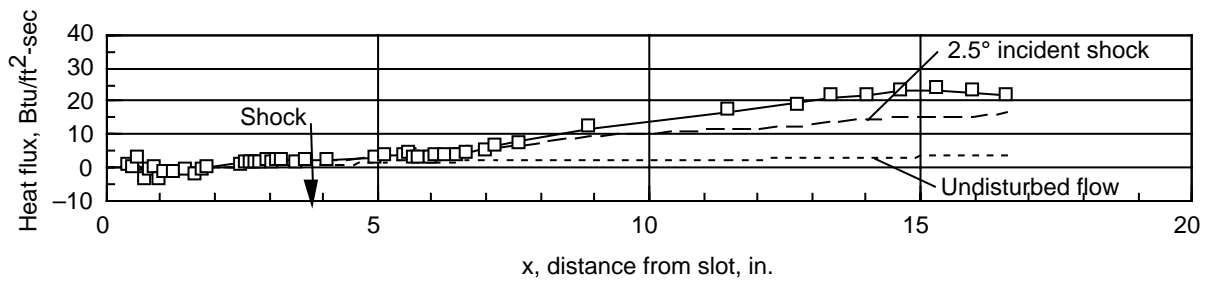
(a) Position 1 ( $y = -0.424$  in.).



(b) Position 2 ( $y = 0.0$  in.).

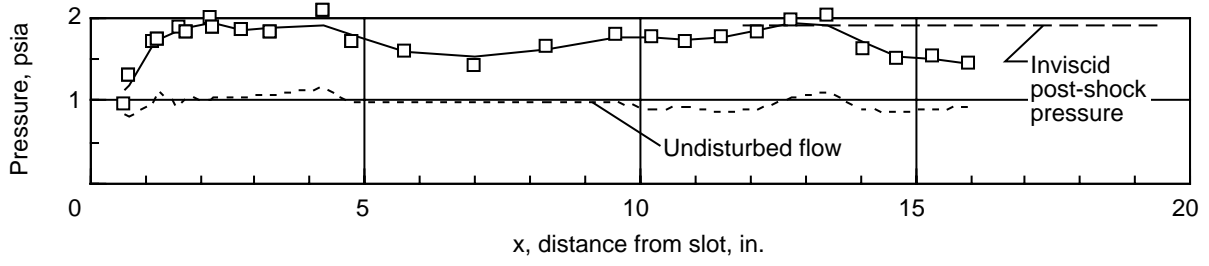


(c) Position 3 ( $y = 0.424$  in.).

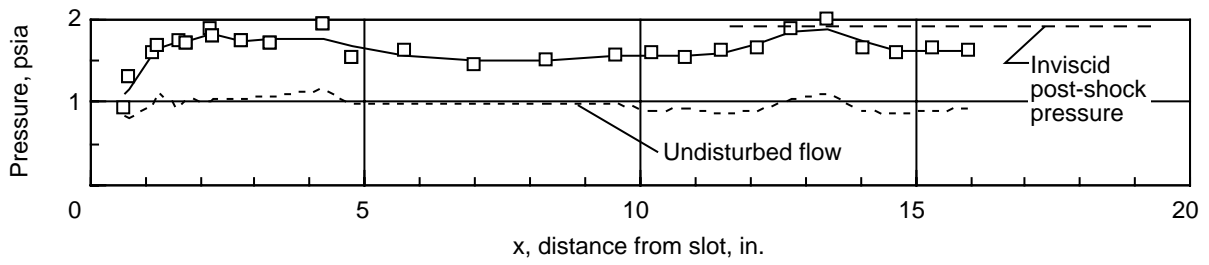


(d) Position 4 ( $y = 0.848$  in.).

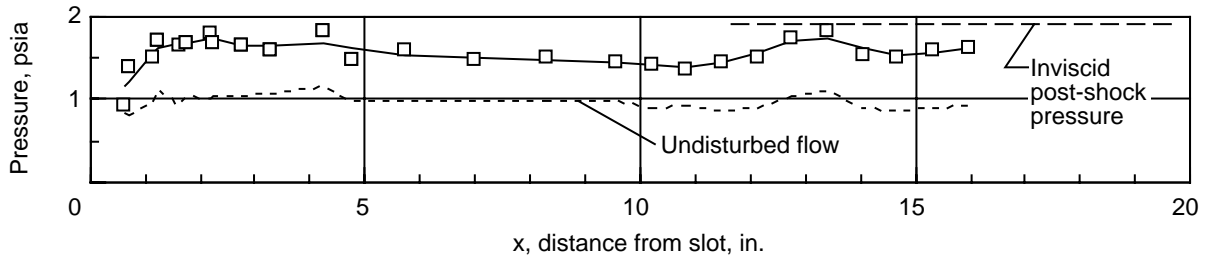
Figure 24. Heat-flux distribution for  $5^\circ$  swept shock with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ).



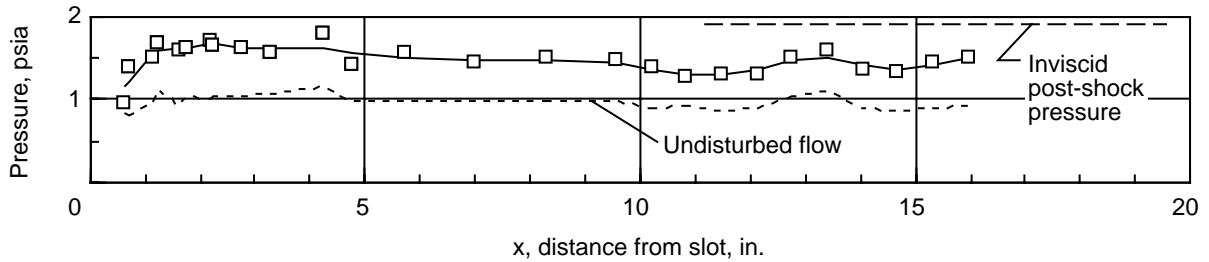
(a) Position 1 ( $y = -0.424$  in.).



(b) Position 2 ( $y = 0.0$  in.).

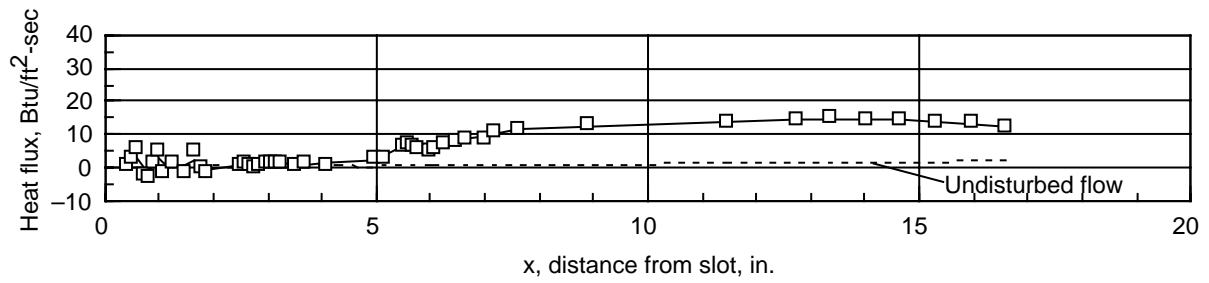


(c) Position 3 ( $y = 0.424$  in.).

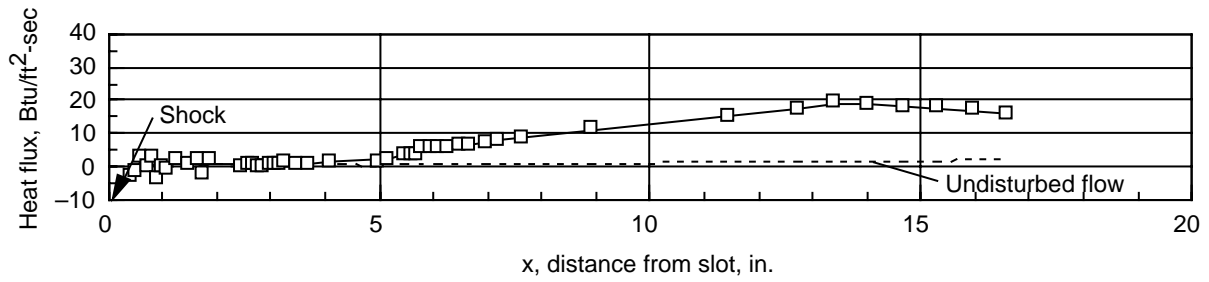


(d) Position 4 ( $y = 0.848$  in.).

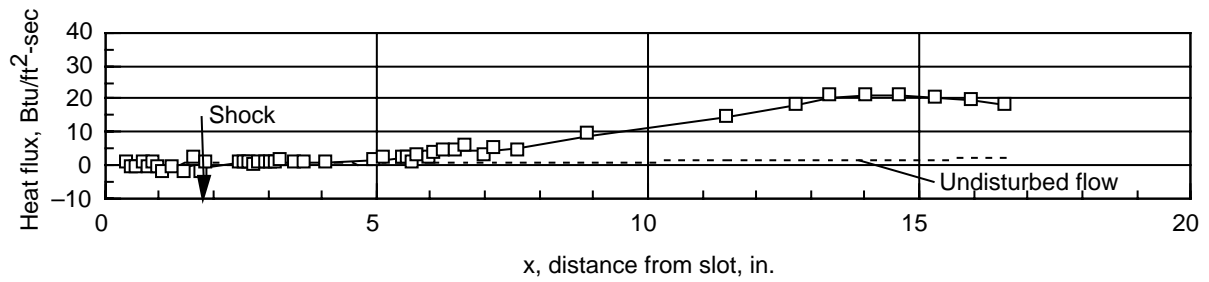
Figure 25. Pressure distribution for  $5^\circ$  swept shock with hydrogen coolant at  $m_c = 0.260$  ( $p_c/p_e = 1.0$ ). (See fig. 5 for shock-instrumentation intersections.)



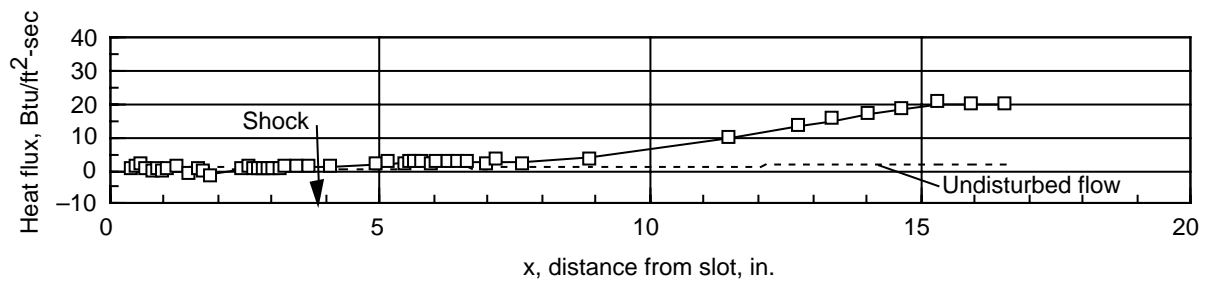
(a) Position 1 ( $y = -0.424$  in.).



(b) Position 2 ( $y = 0.0$  in.).

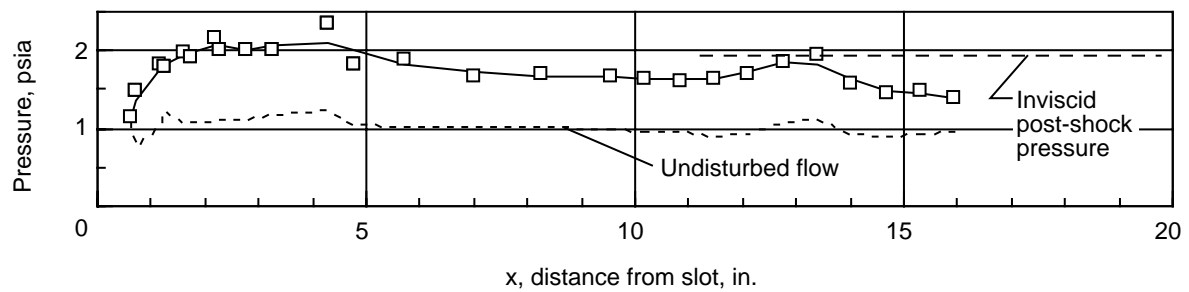


(c) Position 3 ( $y = 0.424$  in.).

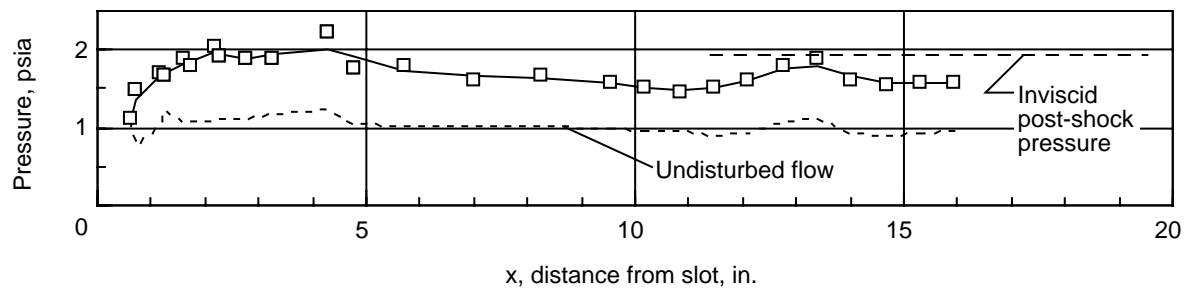


(d) Position 4 ( $y = 0.848$  in.).

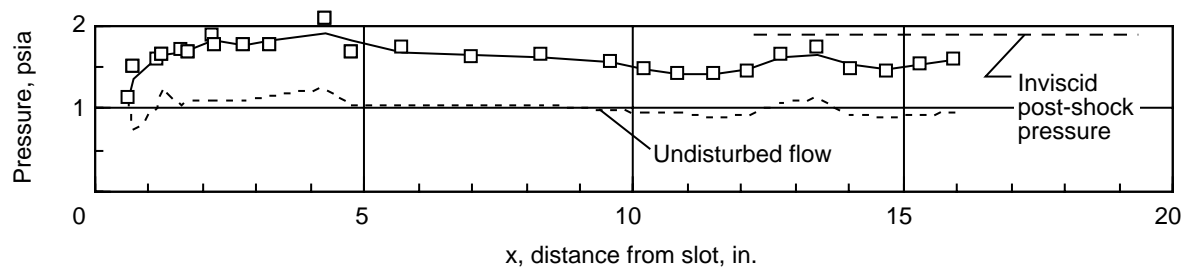
Figure 26. Heat-flux distribution for  $5^\circ$  swept shock with hydrogen coolant at  $m_c = 0.662$  ( $p_c/p_e = 2.0$ ).



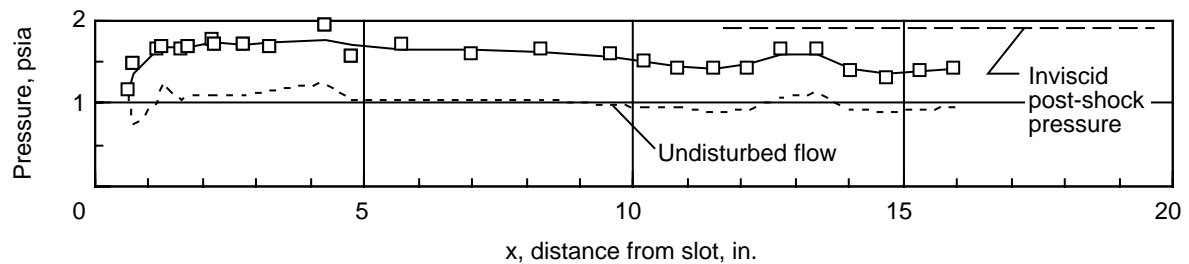
(a) Position 1 ( $y = -0.424$  in.).



(b) Position 2 ( $y = 0.0$  in.).

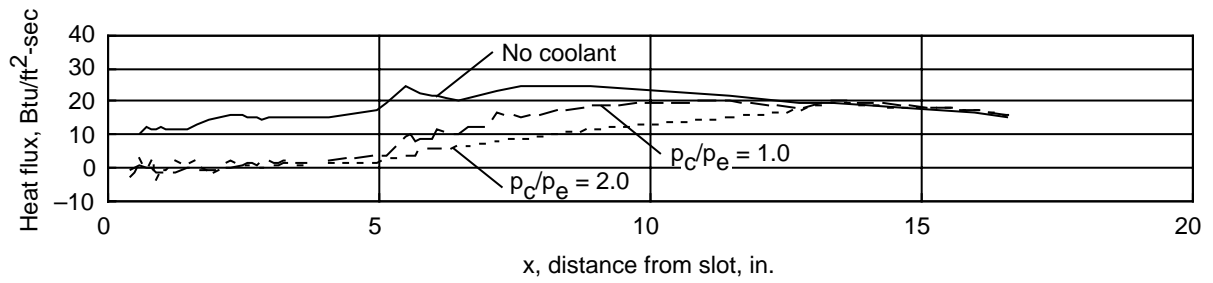


(c) Position 3 ( $y = 0.424$  in.).

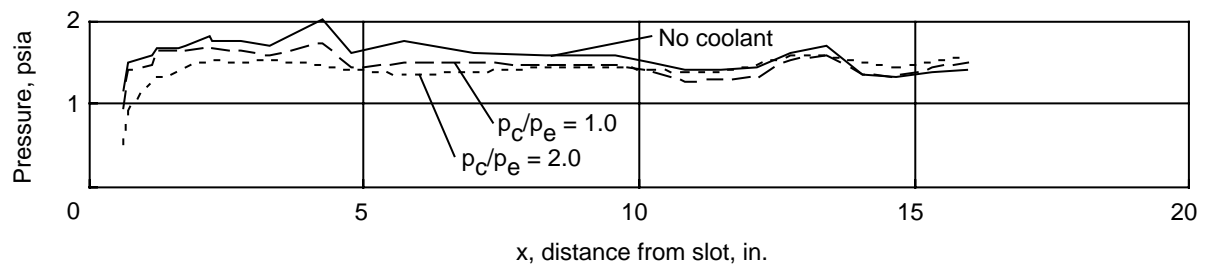


(d) Position 4 ( $y = 0.848$  in.).

Figure 27. Pressure distribution for  $5^\circ$  swept shock with hydrogen coolant at  $m_c = 0.660$  ( $p_c/p_e = 2.0$ ). (See fig. 5 for shock-instrumentation intersections.)



(a) Heat flux.



(b) Pressure.

Figure 28. Composite of heat-flux and pressure coincident data at equivalent shock location.  $y = 0.0$  in.



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